Study of the Behavior of Photovoltaic Systems under the Influence of Shading and Various Bypass Diodes Configurations

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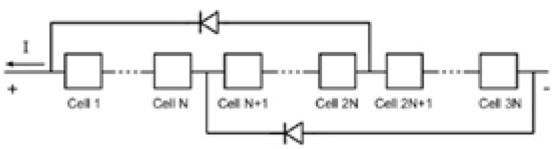
Abstract: ***The I-V characteristic curve of a photovoltaic module is impacted by shadows, depending on the shaded area of the PV module and the radiation received by the shaded areas. Another factor influencing the shape of the I-V curve of a PV module is the configuration of the electrical connection between its cells and bypass diodes. Bypass diodes are installed in the modules to prevent power loss when they are shaded or damaged; they also prevent cells from operating near the avalanche zone. This paper investigates the performance of a photovoltaic array, which comprises interconnected modules. Specifically, the configuration with overlapping bypass diodes is analyzed, demonstrating that completely or partially shaded modules may consume some of the power generated by other modules in the PV array. This effect is also evident in low-power PV arrays. In such cases, the power dissipated by a diode is small, but with many diodes, the cumulative power dissipation can be comparable to the power produced by various PV modules. Additionally, this article explores the impact of the inverter on Maximum Power Point (MPP) tracking.***

Keywords: Behavior PV arrays, shadows, bypass diode

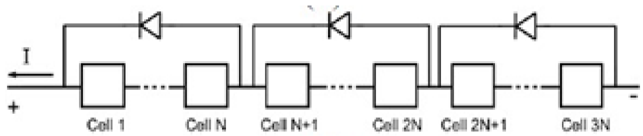
1. Introduction

One of the primary causes of energy generation losses in photovoltaic systems is partial shading on photovoltaic (PV modules). These PV modules consist of photovoltaic cells (PV cells) connected either serially or in parallel, with diodes included in various configurations. The curve of a PV cell varies based on the received radiation [1] [2] and its temperature. Additionally, the modules have diodes that provide an alternative path for current flow when a sufficient number of cells are shaded or damaged. Two typical configurations of bypass diodes exist: [3] overlapped (Fig. 1a) and non-overlapped (Fig. 1b). It is important to note that analyzing modules with overlapped diodes is more complex due to the potential for different paths for current flow.

While many papers analyze the behavior of photovoltaic PV cells under partial shadowing [4][5][6], taking the diode into account, only a few consider the significance of diode configuration [3]. This article investigates the individual behavior of a PV module and a photovoltaic array of PV modules (PV array) connected to an inverter, considering shadows in both scenarios.



(a)



(b)

Figure 1: Bypass diodes (a) overlapped (b) no-overlapped

2. Development

2.1. Behavior of a PV Cell

In order to analyze the behavior of a partially shaded module, it is essential to have the following information:

- The forward and reverse biased curves of the cells (see Fig. 2).
- The radiation-dependent curves of the cells (see Fig. 3).
- The curves of the bypass diodes.

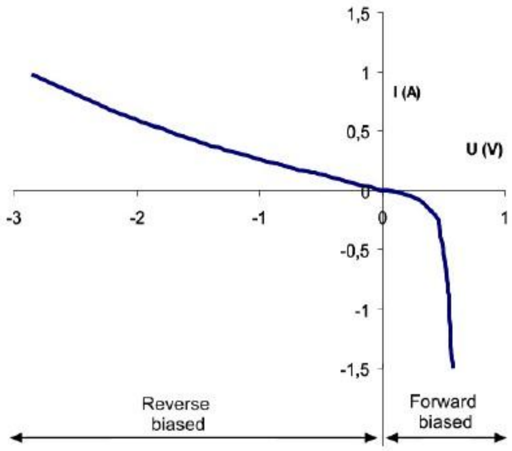


Figure 2: Curves of a cell forward and reverse biased PV cell for 0 W/m^2

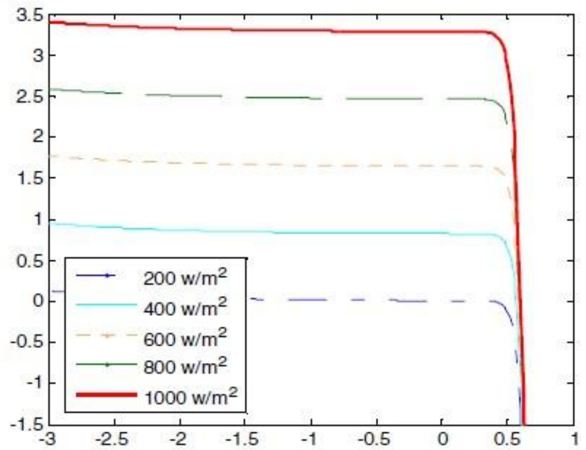


Figure 3: Curves of a PV cell for different solar radiations

2.2. Behavior of a PV Cell array

When shadows fall over a PV module, it is crucial to consider the behavior of a PV cell in its reverse zone (negative voltage), as shaded PV cells can become reverse biased. In Fig. 4a, it is illustrated that for a current of 2A, a sunny cell has a voltage of 0.55 V, while a shaded one has -5.5 V. If a bypass diode is in parallel with 12 PV cells serially connected, with one of them shaded, the group voltage will be 1.1 V (Fig. 4.b), and thus, the diode will not conduct because it is reverse biased. Conversely, for current values exceeding 3A, the group voltage will be negative, and the currents will flow through the diode as it is forward biased.

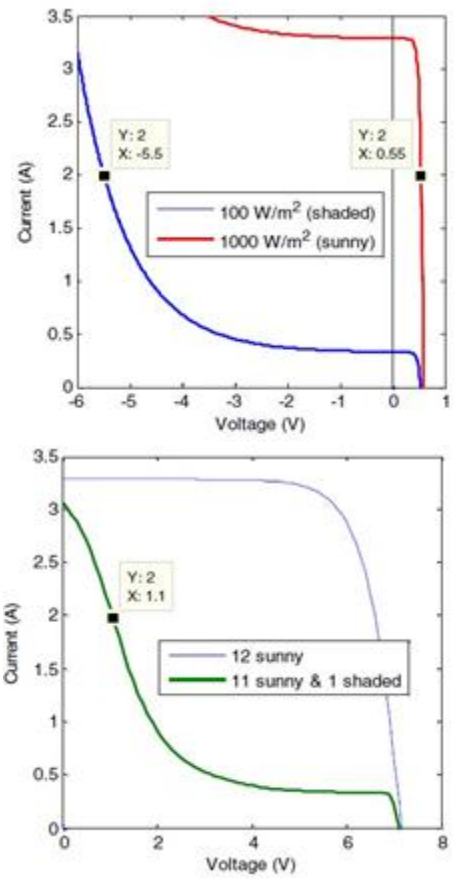


Figure 4: Curves of individual sunny and shaded cells (a) and curves of 12 sunny (1000W/m^2) serial cells and 11 sunny and 1 shaded (100W/m^2) serial cells (b)

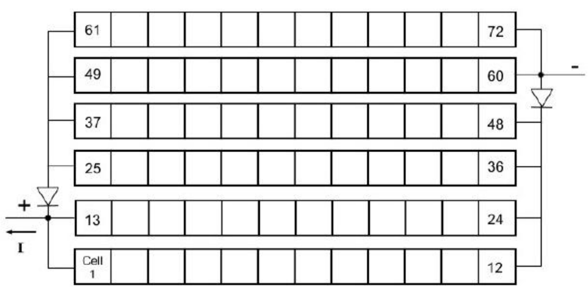
2.3. Behavior of a PV module

A PV module is composed of arrays of PV cells, with bypass diodes connected in parallel. The arrangement of these connections defines the I-V curve of the PV module when shadows are present. In this paper, a PV module is configured with 72 PV cells, organized into 6 rows of 12 PV cells each. The configurations are as follows:

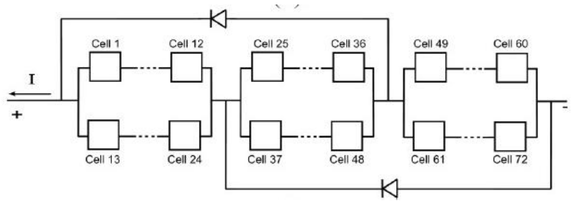
1) Overlapped bypass diodes
2) No-overlapped bypass diodes

a) Overlapped bypass diodes

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



(a)



(b)

Figure 5: Photovoltaic module (a) physical distribution (b) electrical scheme with overlapped diodes

The I-V and P-V curves of the PV module for solar radiations of 1000 and 100 W/m² are depicted in Fig. 6. When the PV module is shaded, the negative voltage at the working point can be 1/3 of its open-circuit voltage, and the power consumed may surpass 1/3 of the peak power of the PV module.

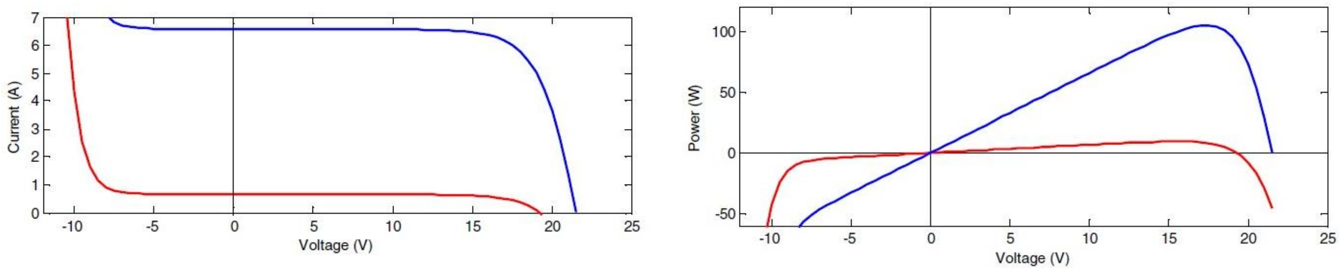


Figure 6: I-V and P-V curves of a PV module with overlapped bypass diodes

To investigate the typical behavior of the PV module, a simulation of progressive shading will be conducted from the bottom PV cell row to the top one. This practical approach is relevant as situations may arise during sunrises and sunsets where the PV module experiences shading similar to the simulated scenarios. There are three possible paths for the majority of electrical current (see Fig. 7). The path is contingent on the forward biasing of the diodes, and the diode biasing, in turn, hinges on the shading of the PV cells. When both diodes are forward biased, the modules of the two central series are responsible for a significant power drain. Each of these paths represents a point on the I-V and P-V curves (see Fig. 8).

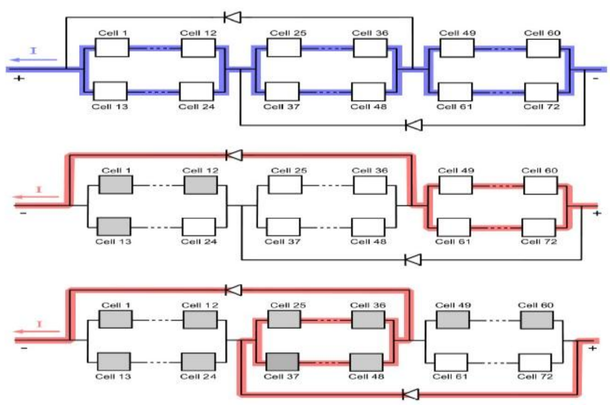


Figure 7: Electrical current in PV modules with overlapped bypass diodes

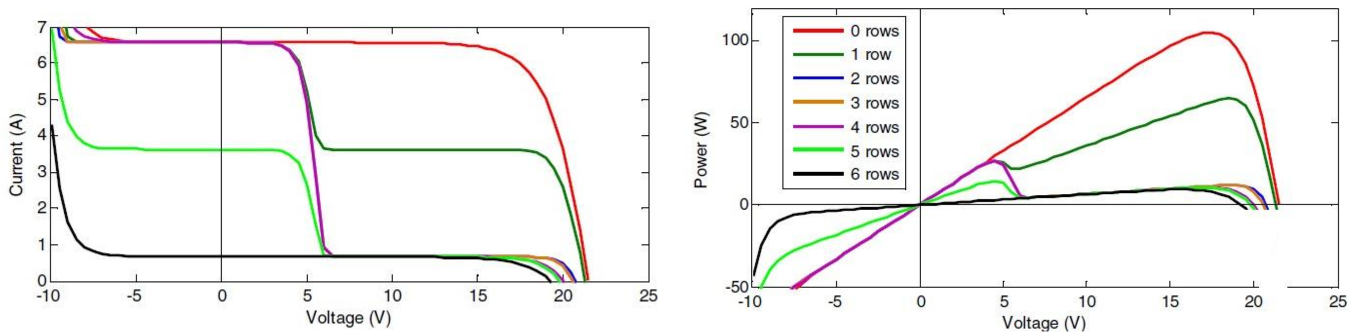


Figure 8: I-V and P-V curves of a PV module with overlapped bypass diodes progressively shaded

b) No-overlapped bypass diodes

In the second analyzed configuration, the PV module features non-overlapped bypass diodes while maintaining the same physical distribution of the PV cells. In this scenario, the electrical circuit comprises 3 series, each containing 24 PV cells, with each series having a bypass diode (refer to Fig. 9). Due to this configuration, the I-V curve of the P-V array exhibits twice the open-circuit voltage and half the short-circuit current compared to a PV module with overlapped diodes but with the same peak power.

Furthermore, when the PV module is reverse biased, both its voltage and power consumption are lower than in the previous case. However, in situations of low power generation, this consumption may be significant due to the power consumption of the forward-biased diodes (3.9 watts/diode).

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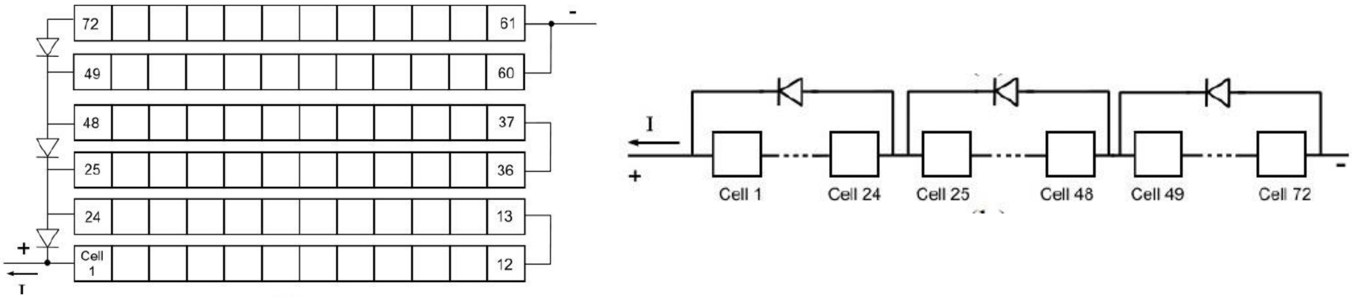


(a) (b)

Figure 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).

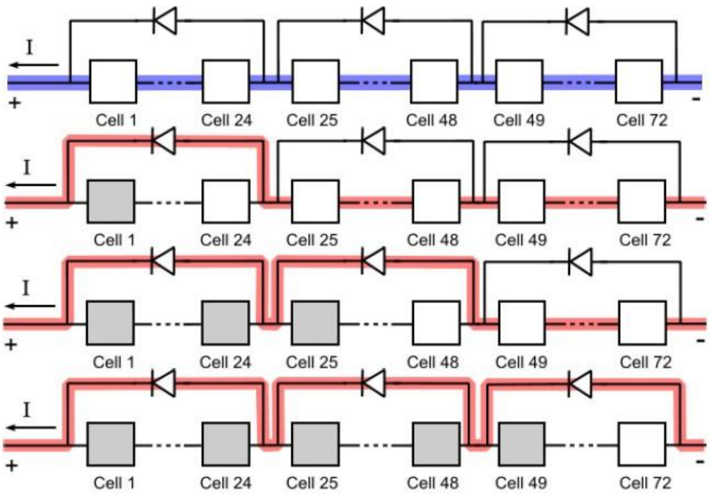


Figure 10: Current flow in PV modules with no-overlapped bypass diodes

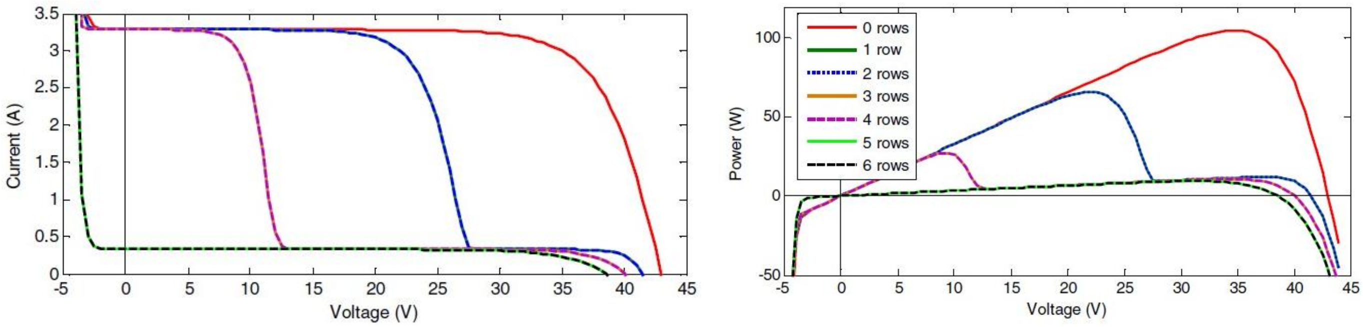


Figure 11: I-V and P-V curves of a PV module with no-overlapped bypass diodes progressively shaded

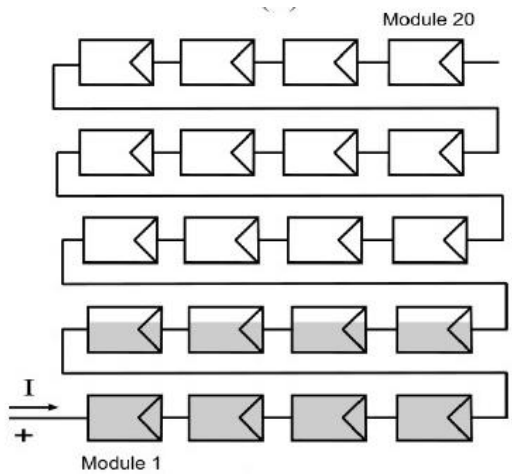
2.4. Behavior of a PV array

In an unshaded PV array with no deteriorated PV modules, all the PV modules share the same Maximum Power Point (MPP). However, when certain PV modules are either fully or partially shaded, the I-V curve of the PV array undergoes changes, leading to potential variations in the MPP for each PV module. This disparity can result in energy losses. Importantly, the energy loss attributed to shadows on the PV modules is not necessarily proportional to the shadow's area; it can be considerably higher. The losses in a PV array are primarily dependent 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 W/m^2 and the shaded ones by 100 W/m^2 (Fig. 13).

(a)



(b)

Figure 12: PV array (a) photo, (b) electrical scheme

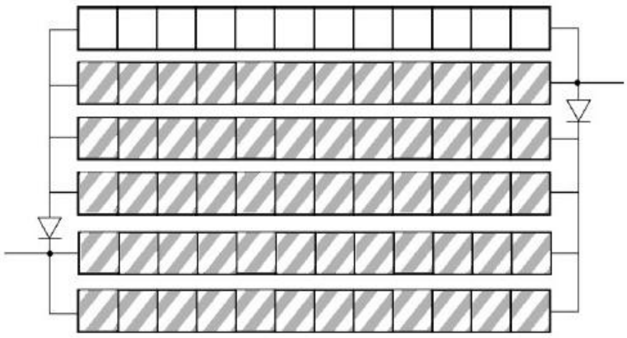


Figure 13: PV module partially shaded

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 calculation of the power produced by each PV module from the working point of the PV array is illustrated in Fig. 14. The curves in the right column depict the I-V and P-V curves of the PV array: the dashed line represents the curve for an unshaded PV array, while the solid line represents the curve for the current example. The curves in the left column correspond to the curves of individual PV modules: the blue curve is for an unshaded PV module, the red curve is for a partially shaded PV module, and the green curve (dotted or solid) is for a totally shaded PV module. The detailed results are presented in Table 1, where a negative value of power (P) signifies power consumption.

Table 1: 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°	*P(W)*	*n°*	*P(W)*	*n°*	*P(W)*
A	784.9	12	103.7	4	-58.5	4	-56.3
B	1164	12	104.9	4	-11.82	4	-11.82
C	1164	12	104.9	4	-11.80	4	-11.80

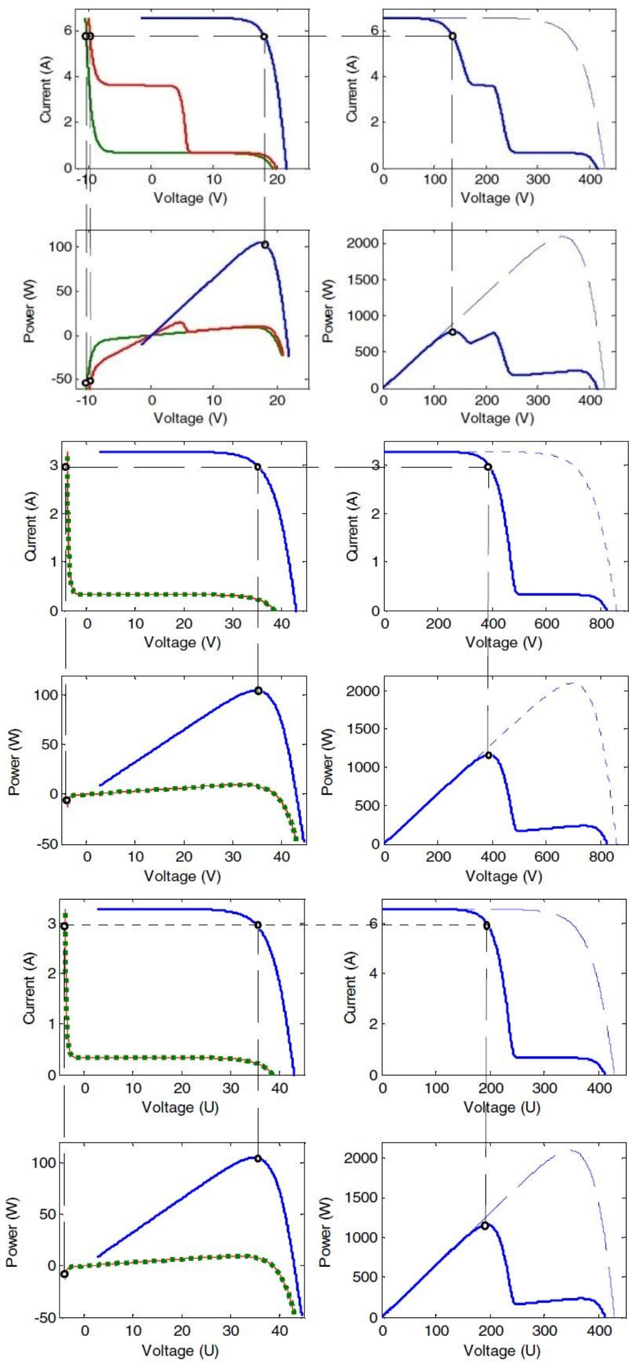


Figure 14: PV and I-V curves of PV modules (left columnt) and PV arrays (right column)

A simulation similar to that in the previous section has been conducted to analyze the behavior of PV arrays at sunrise and sunset. Figure 15 displays the I-V and P-V curves of the PV array when complete rows of PV cells are shaded. The PV module layout consists of 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

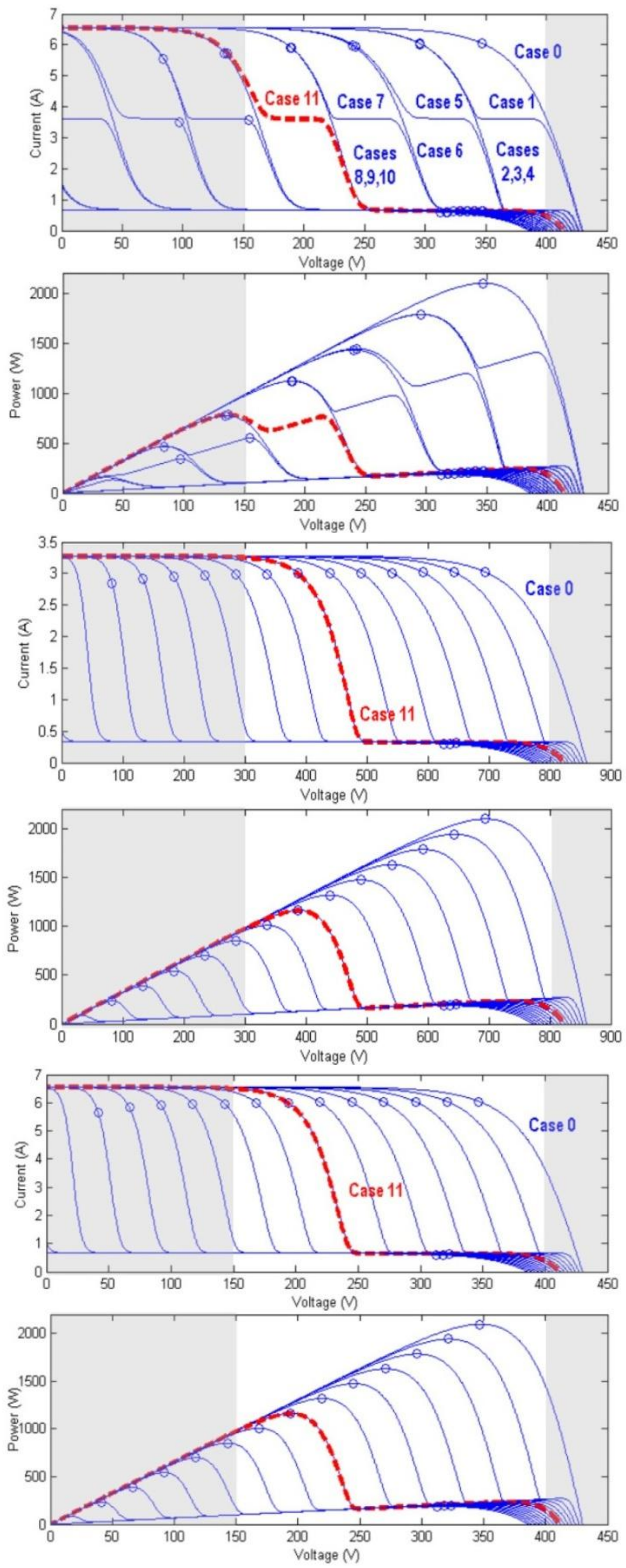


Figure 15: I-V and P-V curves of PV arrays progressively shaded

Each case is depicted by a curve, and it appears that there are fewer curves than the actual number of cases. This discrepancy arises because some of the curves are closely situated and cannot be clearly distinguished. The highlighted curves correspond to the case illustrated in Fig. 12, where the first eleven rows at the bottom of the installation are shadowed (Case 11).

The grey zones on the graph indicate areas where selected inverters cannot operate. Therefore, if the Maximum Power Point (MPP) falls within this zone, the inverter cannot reach it. The selected inverters have a voltage operating range of 150 V to 400 V for Configurations A and Configuration C, and 300 V to 800 V for Configuration B. The circles on the graph represent the MPP for each case.

2.5. Limits of inverter

An inverter connected to the PV array may not always attain the Maximum Power Point (MPP) due to its voltage operating range and the MPP tracking algorithm. In Fig. 16, where the P-V curve of Case 17 is depicted, there are four types of points where the inverter might believe it has reached the MPP. However, the inverter can only operate in three of them. The absolute maximum is beyond its working voltage range.

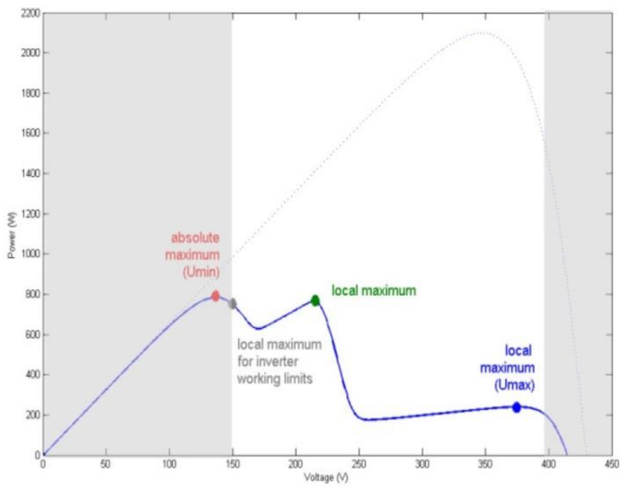


Figure 16: Maximum and local power points of a P-V curve.

In Fig. 17, the various types of Maximum Power Points (MPPs) are displayed against the number of inferior rows shaded in the PV array for different configurations. Upon examination, in Configuration A, power losses can reach 40%, whereas in Configurations B and C, the losses are limited to 20%. Interestingly, the same amount of power is generated when 12 rows are shaded in Configuration A, 20 rows in Configuration B, and 16 rows in Configuration C. In other words, PV arrays with bypass diodes (Config. A) are more prone to power losses due to the shadowing of their PV modules.

Fig. 18 illustrates the absolute MPP achieved in the three PV array configurations, highlighting the similarity between Configuration B and Configuration C.

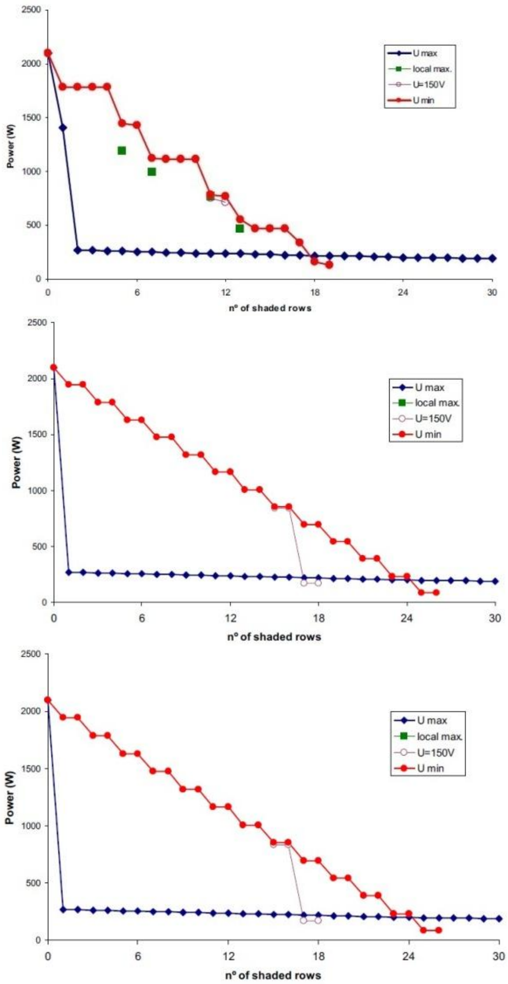


Figure 17: MPPs of the PV arrays in function of the number of bottom rows shaded

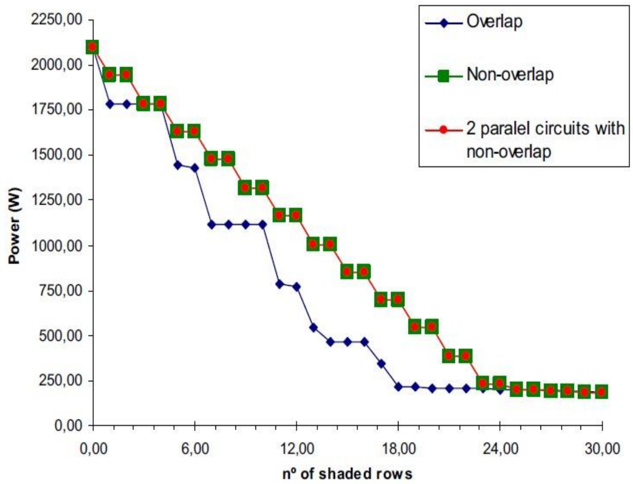


Figure 18: Maximum MPPs of the PV arrays in function of the bottom rows shaded

3. Conclusion

A study on the behavior of isolated PV modules and PV arrays with different configurations of their bypass diodes has been conducted. It has been demonstrated that losses resulting from shadows are contingent on the bypass diode configuration of the PV modules.

In PV modules with overlapped diodes, power losses can amount to one-third of their peak power. This is because, in addition to the bypass diodes, one-third of the PV cells can also consume power. On the other hand, in PV modules with non-overlapped bypass diodes, power losses are solely attributed to the power consumption of the diodes. Nonetheless, these losses would only be significant if there were an excessive number of bypass diodes and shaded PV modules.

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Author Profile

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