MATHEMATICAL MODELLING AND SIMULATION OF A PARTIALLY SHADED PHOTOVOLTAIC MODULE

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Abstract
Photovoltaic installers are very much concerned with photovoltaic systems working under shaded conditions and this has led to detailed research in this domain. We show in this paper that the electrical power produced by a partially shaded module is greatly reduced as compared to when operating under its optimal conditions. With the aim of having a better understanding of the impact of shading on the production of a photovoltaic module and thereby estimating the economic efficiency of a photovoltaic system, we have also worked on the modelling and simulation of a partially shaded photovoltaic module. The method used consists of first, modelling the current-voltage characteristics of the photovoltaic cells independently and then, summing them up according to the electrical configurations of the module. The results show that the bypass diodes reduce negative effects of shading on the production of electricity of a module. An estimation of the power loss is made at the maximum power point under shaded conditions.
Key words: photovoltaic cells, group of PV cell, photovoltaic module partially shade, bypass diode, blocking diode, Maximum power point (MPP).

1. Introduction
In order to promote the use of photovoltaic systems, it is important to carefully examine the power losses of these systems under partially shaded conditions. Indeed, the shading of a PV module implies that PV cells, which constitute it, work in different illumination conditions. The immediate consequence of this is not only a significant reduction of the power generated by the PV module as compared to when operating at optimal conditions but also, a risk of destruction of the PV module if it lacks a protecting system.

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Under these real operating conditions, the PV cells are no longer identical and the I-V characteristics curve is thus no longer easy to calculate and depends on the behaviour of each PV cells. A detailed analysis of the electrical behaviour of a partially shaded PV module therefore needs to take into account each cell's I-V characteristics, protecting diodes (bypass and blocking) and the various existing series and parallel connections of the cells. This complex combination is mainly characterized by the existence of non-linear equations which are difficult to solve. In order to solve these equations, most authors used the Newton-Raphson's method [1], [2], [3], [4]. Moreover, this method presents an advantage in that, a rapid quadratic convergence of the initial values is obtained with results closed to the roots in such a way that a good solution could be gotten in only a few iterations steps. Many authors have already studied the behaviour of a partially shaded PV module [5], [6], however, in most cases, the PV cells are either completely illuminated or completely shaded In this paper we address the problem of considering that the shadow on the module affects several PV cells at different shading rates.

The mathematical modelling and the behaviour of a partially shaded PV module at its maximum power point (MPP) is of great importance. For this reason, so many algorithms were developed to study the maximum power point tracking (MPPT) [7], [8], [9], [10] where the converters make a dynamic research so that the PV system functions best at this point. In addition, the MPP is determined by searching for the maximum point on the P-V curve or by searching for the maximum value of the IV product in the characteristic I-V curve. This work is of great importance in that; a partially shaded module produces a lower power output as compared to that produced by an illuminated module. It is in this context that different scenarios have been developed to show that the power at the maximum power point is sensitive to a shadow casted on a module when some of the cells in groups are shaded. This work portraits the importance of protection diodes to abate the impact of the shadow on the electrical production of a PV module. Furthermore, according to the electrical interconnections, two configurations of the PV module are studied; one of which is that consisting of only PV cells connected in series, and the other; a mixed series/parallel connection.

This paper is divided into four sections: Section 2 describes the method adopted to study the I-V characteristics of the cells at variable shaded rates, the grouped cells together with their different electrical connections. The iterative method which is used is also presented. Section 3 analyses the behaviour of a module with 36 cells subjected to four different shading cases. Another analysis of a module with 72 cells in a mixed connection is also described in three different shading cases. The last section 4 is the conclusion of this work.

2. Method

The proposed method is based on the addition of the I-V characteristics of each PV cell compositing the module. This process is divided into four (04) main parts according to the electrical interconnections (series and parallel) of the cells in the module as shown in figure1:

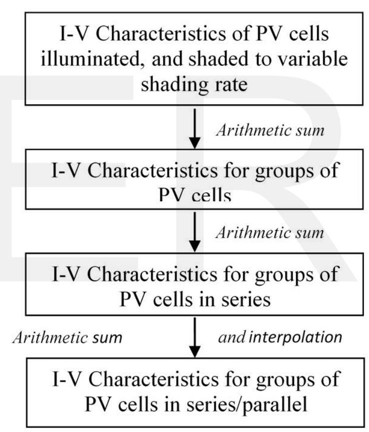

Fig. 1. Modelling strategy of a PV module in faulty operation.

2.1. I-V characteristics of PV cells and mathematical solving method

The I-V characteristic of an illuminated cell is described by the nonlinear equation (1) [7].

$$I_1 = I_{ph1} - I_0\left[\exp\left(\left(q/AkT\right)\left(V_{1,cell} + I_1.R_s\right)\right) - 1\right] - \left(V_{1,cell} + I_1.R_s\right)/R_{sh} \quad (1)$$

where, R_{sh} is the cell shunt resistance, R_s the cell series resistance, and q is the electron charge, k is Boltzmann constant, T is the temperature cell, I_0 is the diode reverse bias saturation current, A is the diode ideality factor, I_{ph1} is the current generated by the incident light. The equation of the I-V characteristic of a partly shaded cell, according to Bishop's model is given by the relation (2). [2, 3, 4, 11]:

$$I_2 = I_{ph2} - I_0\left[\exp\left(\left(q/AkT\right)\left(V_{2,cell} + I_2R_s\right)\right) - 1\right] - \left(\left(V_{2,cell} + I_2R_s\right)/R_{sh}\right)\left[1 + a\left(1 - \left(V_{2,cell} + I_2R_s\right)/V_{br}\right)^{-n}\right] \quad (2)$$

where a is the Bishop's fitting coefficient ; n the exponent of avalanche breakdown; V_{br} the cell junction breakdown voltage .

I_{ph1} and I_{ph2} are the photocurrents of illuminated and shaded PV cells, respectively. Equation (3) links these terms [5], [11]:

$$I_{ph2} = \alpha . I_{ph1} \quad (3)$$

where α is the shading coefficient of value between 0 and 1; when α= 1 the cell is completely illuminated and when α = 0 the cell is completely shaded.

Indeed, the shading coefficient is defined as the ratio between the solar radiation received by a shaded cell (module, array) (G_{sha}) and that of an illuminated cell (G_{ill}) as indicated by (4) [4], [12]:

$$\alpha_i = 1 - G_{sha}/G_{ill} = 1 - \zeta_i/A \quad (4)$$

where ζ_i is the shaded area of the cell and A, the total surface area of the cell.

2.2. Mathematical model resolution

The I-V characteristic is obtained by imposing the current over a given range, which enables the search for the corresponding voltage according to (5):

$$I_{cell} = I_{imposed} \quad (5)$$

$$I_{cell} \xrightarrow{f\left(I_{cell}, V_{cell,i}, \alpha_i\right) = 0} V_{cell,i}$$

where $f(I_{cell}, V_{cell,i}, \alpha_i)$ is a non-linear implicit function, associated with i^{th} PV cell and α its corresponding shading coefficient defined by (6).

$$f(I, V_{cell,i}, \alpha_i) = \begin{cases} -I + \alpha_i . I_{ph} - I_0\left[\exp\left(\left(q/AkT\right)\left(V_{cell,i} + I.R_s\right)\right) - 1\right] - \left(V_{cell,i} + I.R_s\right)/R_{sh} = 0 & if\ \alpha_i = 1 \\ -I + \alpha_i . I_{ph} - I_0\left[\exp\left(\left(q/AkT\right)\left(V_{cell,i} + I.R_s\right)\right) - 1\right] \\ -\left(\left(V_{cell,i} + I.R_s\right)/R_{sh}\right)\left[1 + a\left(1 - \left(V_{cell,i} + I.R_s\right)/V_{br}\right)^{-n}\right] = 0 & if\ \alpha_i \neq 1 \end{cases} \quad (6)$$

The value of the voltage $V_{cell,i}$ across the cell indexed i for a given current (I) is obtained by using the Newton-Raphson method, which offers considerable advantages over other numerical methods. Moreover, it has the advantage of a rapid quadratic convergence of the initial values near the roots so as to obtain a good solution calculated in a few iterations. The Newton-Raphson iterative method enables an approach to the function $f(V_{cell}, I, \alpha_i) = 0$, solution to (7):

$$V_{cell,i}(k) = V_{cell,i}(k-1) - f\left(V_{cell,i}(k-1), I, \alpha_i\right) / \left(\partial f\left(V_{cell,i}(k-1), I, \alpha_i\right)/\partial V_{cell,i}\right) \quad (7)$$

where k is the number of iterations. This iteration is performed once an initial value is given to $V_{cell,i}(1)$. The iteration will stop when two consecutive values of the voltage satisfy the following condition:

$$\left|V_{cell,i}(k) - V_{cell,i}(k-1)\right| \prec \varepsilon \quad (8)$$

where ε is very close to zero. The derivative of the characteristic function $f(V_{cell}, I, \alpha_i)$ with respect to the voltage V_{cell} is given by relation (9):

$$\partial f\left(V_{cell,i}(k-1), I, \alpha_i\right)/\partial V_{cell,i} = \begin{cases} (q.I_0)/(AkT)\exp\left(\left(q/AkT\right)\left(V_{cell,i}(k-1) + I.R_s\right)\right) + 1/R_{sh} & if\ \alpha_i = 1 \\ (q.I_0)/(AkT)\exp\left(\left(q/AkT\right)\left(V_{cell,i}(k-1) + I.R_s\right)\right) + 1/R_{sh} + \\ \left(a/R_{sh}\right)\left(1 - \left(V_{cell,i}(k-1) + I.R_s\right)/V_{br}\right)^{-n} \\ +(a.n/V_{br})\left(\left(V_{cell,i}(k-1) + I.R_s\right)/R_{sh}\right).\left(1 - \left(V_{cell,i}(k-1) + I.R_s\right)/V_{br}\right)^{-n-1} & if\ \alpha_i \neq 1 \end{cases} \quad (9)$$

2.3. I-V characteristics of a group PV cells

A group of PV cells is a set of PV cells in series (12 cells in our study) on which is mounted one bypass diode as shown in Figure (2) [2], [3], [13];

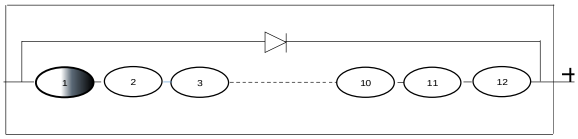

Fig. 2. Setting up a group of PV cells illuminated at 50%.

These bypass diodes can help to avoid the hot spot effect which usually occurs when one cell among the series connected cells is shaded. For most manufacturers, a module made up of 36 cells is equipped with three (03) bypass diodes [13], that is, one diode in a series of 12 PV cells. As reported in the literature [3], [14] a few modules also have one (01) bypass diode for eighteen (18) cells. The number of cells protected by a bypass diode can thus vary between different module manufacturers.

When the bypass diode is active, it happens when one or more PV cells are crossed by a current greater than the short circuit current, the voltage at the terminals of the group is zero if the sum of the voltages of all cells is negative. We then have the relation (10):

$$V_{group,j} = \begin{cases} \sum_{i=1}^{N_{cells}} V_{cell,i} & if \quad \sum_{i=1}^{N_{cells}} V_{cell,i} \geq 0 \\ 0 & if \quad \sum_{i=1}^{N_{cells}} V_{cell,i} \leq 0 \end{cases} \quad (10)$$

$$I_{group} = I_{bypass} + I_{cell} = I_{fixed}$$

Figure 3 is a simplified electrical circuit of a group of PV cells having different shading rates.

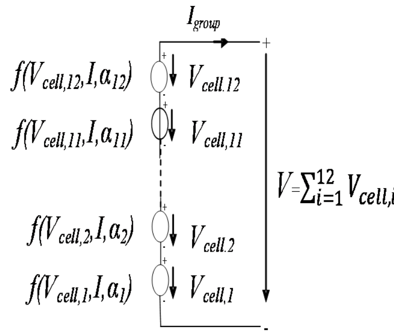

Fig. 3. A simplified electrical circuit for a group of PV cells shaded at different rates.

Thus, for a (01) partially illuminated cell (at 50%) and eleven (11) cells completely illuminated (see Figure 2), the I-V characteristic curve for the 12 grouped PV cells is shown in Figure 4.

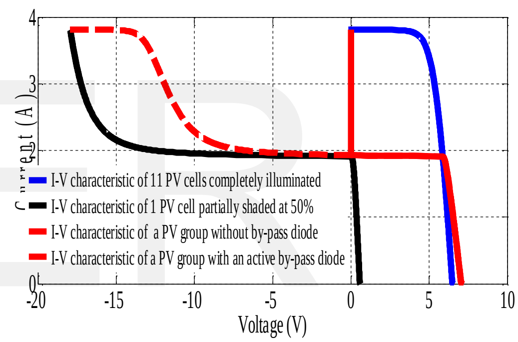

Fig. 4. I-V Characteristic of a group of PV cells with bypass diode.

2.4. Series connection of several groups of PV cells

In order to increase the voltage at the terminals of the PV module, several groups of cells are connected in series. These series connection form the modules we most often encounter. Thus, the current flowing in a module is the same as the one that circulates in the various groups; while the sum of the voltages across the different group of cells provides the voltage of the module as depicted in Figure 5 and (11):

$$I_{module} = I_{group} \quad (11)$$

$$V_{\text{module}} = \sum_{i=1}^{N_{group}} V_{group,i}$$

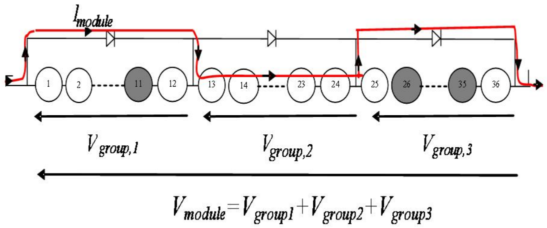

Fig. 5. An implicit power circuit of a module.

Figure (6) shows how the I-V characteristic curves of different PV cells groups are summed up to give the I-V characteristic of a PV module.

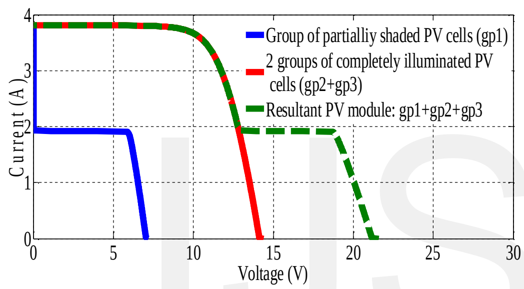

Fig. 6. IV characteristic of a PV module made of 3 groups with one in a poor condition.

2.5. Parallel PV cells

Some PV modules have mixed interconnections (series-parallel). Thus, in order to increase the current of a module several strings (of cells) can be mounted in parallel in the module. A blocking diode is connected in series in the string with the role to protect the group of PV cells against the negative currents that may be generated during different connections in parallel strings. A module of 72 PV cells may for example, be mounted in two (02) parallel strings of 36 cells each as shown in Figure 7.

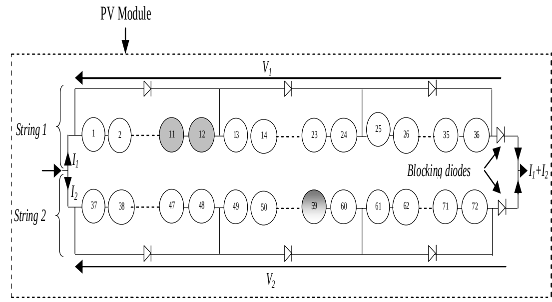

Fig. 7. Implicit electrical circuit for a module with two strings.

When some of the PV cells are shaded, the generated currents and voltages at the terminals of each string connected in parallel no longer have the same values. However since the voltages across the string when put in parallel must be equal; then, the current in each string must be constant. To solve this problem, we proceed as follows:

-We will fix the module voltage value:

$$V_{\text{module}} = V_{fixed} \quad (12)$$

- The value of the current of the string *k* after the parallel connection, may be obtained from an interpolation of the I-V characteristic of the string ($I_{string,k}$, $V_{string,\ k}$) to the expected value of the voltage of the module, satisfying the constraint that the voltage should be the same for each string [3], [4]:

$$I_{string,k} = interpolation(V_{module}, I_{string,k}, V_{string,k}) \quad (13)$$

The blocking diode crashes when the voltage of the string *k* becomes lower than the voltage of the module:

$$I_{string,k} = 0 \quad for\ V_{string,k} \le V_{\text{module}} \quad (14)$$

The expression of the module current is then given by (15):

$$I_{\text{module}} = \sum_{k=1}^{N_{branche}} I_{string,k} \quad (15)$$

Figure 8 shows how 2 strings connected in parallel are influenced by a blocking diode.

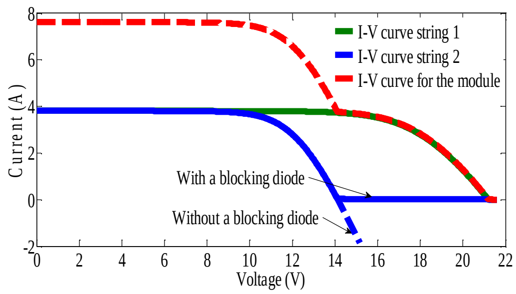

Fig. 8. I-V characteristic of a PV module protected by a blocking diode.

3. Results and Discussion.

In this section, different scenarios are developed according to the geometrical shape of the shadow on the module. We will consider a module made of 3 groups, each comprising of 12 PV cells.

The module used is a Solarex MSX-60 whose necessary characteristics for our simulation are listed in Table 1.

Table. 1. Useful parameters for simulation.

Parameters	Values
Number of cells	36
Number of bypass diodes	3
I_{ph} (A)	3.8119
I_o (A)	$1.859.10^{-7}$
A	1.360
$R_s(\Omega)$	0.180
R_{sh} (Ω)	360.002
A	0.1
N	3
V_{br} (V)	-20

Scenario 1: A single cell is non-illuminated

Figure 9 is a module that consists of 36 PV cells divided into 3 groups each having a bypass diode shunt: Group 1 contains the PV cells numbered from 1 to 12; Group 2 contains the cells numbered from 13 to 24; Group 3 contains the cells numbered from 25 to 36.

In the diagram below, only one cell is shaded and the rest are completely illuminated. The PV cell in bad working conditions is shaded in proportions of 0%, 25%, 50% and 75%.

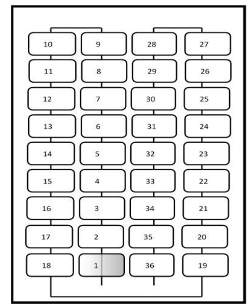

Fig. 9. Geometric location of shade on a PV module.

Figure 10 below shows a module's I-V and P-V characteristic curves for the different shading percentages.

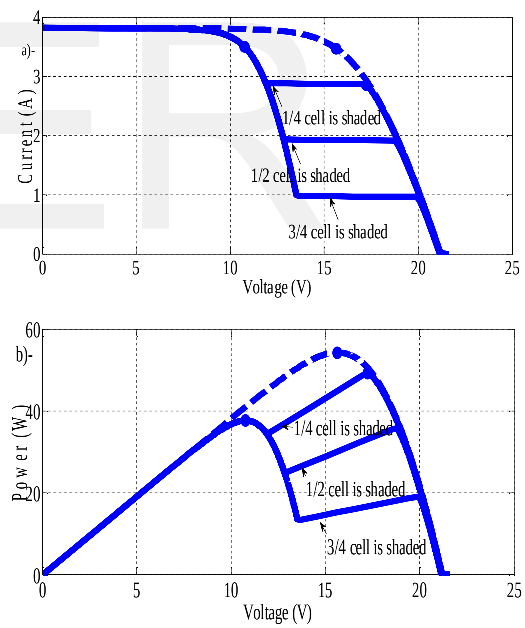

Fig. 10. I-V (a) and P-V (b) characteristic curves for a shaded module in the configuration of figure 9.

In Table 2, we present the optimal power at MPP for different values of the shading coefficient and the power loss resulting from the production of a perfectly illuminated module. We notice here that one shaded PV

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cell can reduce the electrical power of a module to more than 30%. This can be explained by the fact that the current circulating in a group of cells is greatly influenced by the shaded cell (see figure 4). This "defective" group placed in series with two illuminated groups considerably reduces the current of the PV module for a given voltage (see figure 6).

Table. 2. Power losses of a module at MPP for shaded PV cell at different percentages.

Shading coefficient	Power at MPP (W)	Power loss (%)
0.25	37.5822	30.67
0.50	37.5822	30.67
0.75	49.1520	9.32
1	54.2048	0

Scenario 2: Shadow of 5 PV cells with different shading factors

The results of the geometric distribution of the shadow on the module of Figure 11 are as follows: Group1: one (01) PV cell shaded at 95% (cell No. 5), two (02) PV cells shaded at 50% (No. 4 and 5) and nine (09) perfectly illuminated cells; Group 2: one (01) PV cell shaded at 50% (No. 14) and eleven (11) perfectly illuminated cells; Group 3: one (01) shaded cell to 75% (No. 32) and eleven (11) perfectly illuminated cells.

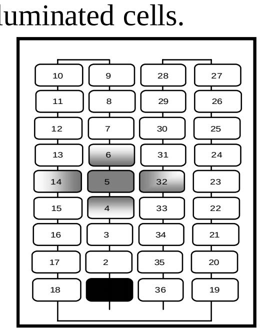

Fig. 11. Location of shade on a PV module.

The I-V and P-V characteristic curves of this module are given in Figure 12. Since the groups of PV cells are shaded, their resultant gives a faulty module whose power at the MPP is 12.3323 W compared to 56.3733 W for a perfectly illuminated module. The power loss at this point is of the order of 78%. In this case, the electrical power produced by the PV module can reduce to more than 80%. This power loss can be explained by the fact that; the three groups of cells are strongly influenced by the number and the I-V characteristic of the shaded cells.

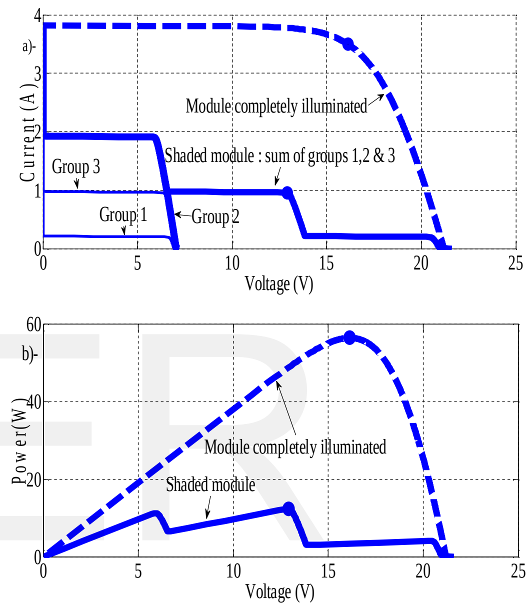

Fig. 12. I-V (a) and P-V (b) characteristic curves for a shaded module in the configuration of figure 11.

Scenario 3: shadow of a larger range on the module

In this example, the shadow extend is greater and the distribution of 9 PV cells are as follows (Figure13):

- Group1: four (04) cells completely shaded (N° 8, 9, 10 and 11), two (02) PV cells partially shaded to 50% (N° 7 and 12) and six (06) perfectly illuminated PV cells;

- Group 2: twelve (12) perfectly illuminated cells;

- Group 3: three (03) PV cells illuminated at 50% and nine (09) illuminated cells.

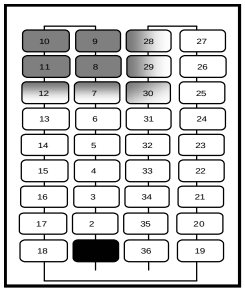

Fig. 13. Location of shade on a PV module.

Figure 14 shows the module's characteristic curves I-V and P-V. The power loss at MPP is about 60% for a calculated power 22.7487 W for the faulty module.

It is noticed that despite the range of the shadow on this module, the power loss is lower compared to scenario 2 (78%). This is explained by the fact that the shadow on the module of scenario 2 affects all of the 3 groups of PV cells. For scenario 3, two (2) groups of the PV cells are in poor conditions and one (01) in good condition. It is the latter group that reduces the losses.

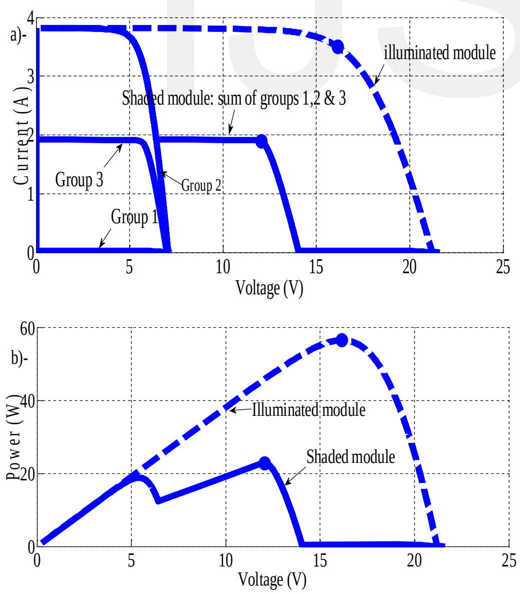

Fig. 14. I-V (a) and P-V (b) characteristic curves for a shaded module in the configuration of figure 13.

Scenario 4: the influence of shadow on a group of a module

In this example, 3 PV cells are completely shaded (α=0) as shown in the following configurations:

- each of the three (3) groups has one (01) shaded PV cell (see Figure 15-a);
- one of the groups contains the three (03) shaded PV cells (see Figure 15-b);
- two (02) groups contain the shaded cells and the third group is completely illuminated (see Figure 15-c).

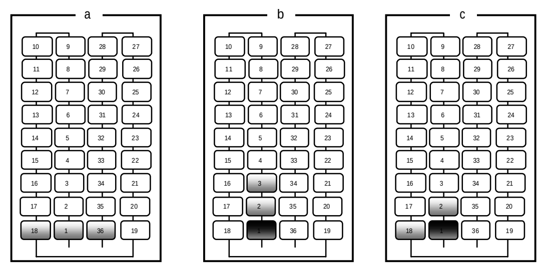

Fig. 15. Location of a PV module with 3 shaded PV cells: the 3 PV cells are divided into 3 groups (a); 3 PV cells belong to a single group (b); 3 PV cells belong to 2 groups (c).

Figure 16 describes the appearance of the module's I-V and P-V characteristic curves in the 3 configurations.

We note that, when each of the 3 groups has a shaded PV cell, the maximum power point is very low. In this case, the power loss is about 99% against 66.7% and 33.3% when the three cells are distributed on two groups of cells, and one cell groups respectively. We can thus retain that any shadow casted on a PV module reduces more of the electrical power produced when it shades many groups of cells.

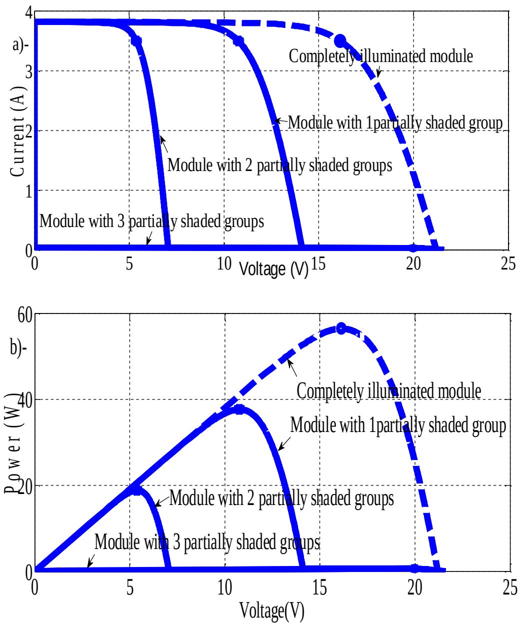

Fig. 16. The characteristic curve I-V (a) and P-V (b) for a faulty module in the configuration of figure 15.

Scenario 5: Module with 2 strings in parallel, one containing a shaded PV cell. Consider a PV module consisting of 2 strings of 36 cells each mounted in parallel. On each string is mounted a blocking diode. Only one cell is shaded (see Figure 17).

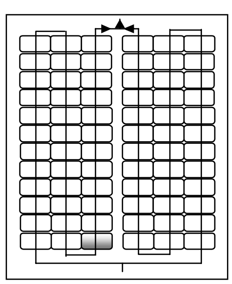

Fig. 17. A module with 2 parallel strings, containing one shaded PV cell.

By varying the shading rate of the shaded cell, we obtained I-V and P-V characteristics of the module as shown in figure18.

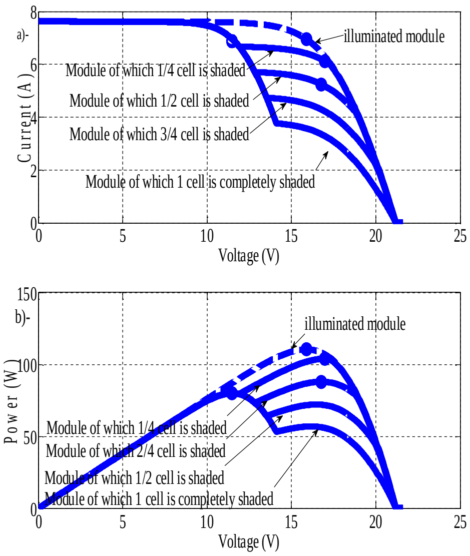

Fig. 18. I-V (a) and P-V (b) characteristic curves for a shaded PV module in the configuration of figure 17.

We notice here that for shadow casted on a cell, the electrical power of the module can reduce to about 27.5%. This power loss slightly smaller than that of scenario 1 can be explained not only by a larger number of PV cells but also by the introduction of a blocking diode which prevents the current coming from the faulty string to go through the other strings.

The energy balance of this module, the maximum power point is given in Table 3.

Table. 3. Energy balance of a module with 2 strings in parallel and one shaded cell.

Shading coefficient	Power at MPP (W)	Power loss at the MPP (W)
0	79.9565	27.5849
0.25	79.9565	27.5849
0.50	87.9530	20.3427
0.75	103.9821	5.8254
1	101.4142	0

Scenario 6: Shadow rate on 5 PV cells on the same string of a PV module at different shading factors.

One of the 2 parallel strings comprises of five (05) shaded PV cells as described in Scenario 2, and the other string is completely illuminated (see Figure 19).

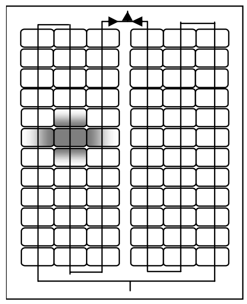

Fig. 19. A 2 strings module of which 1 contains 5 shaded cells.

The I-V and P-V characteristic curves of this module are given in Figure 20.

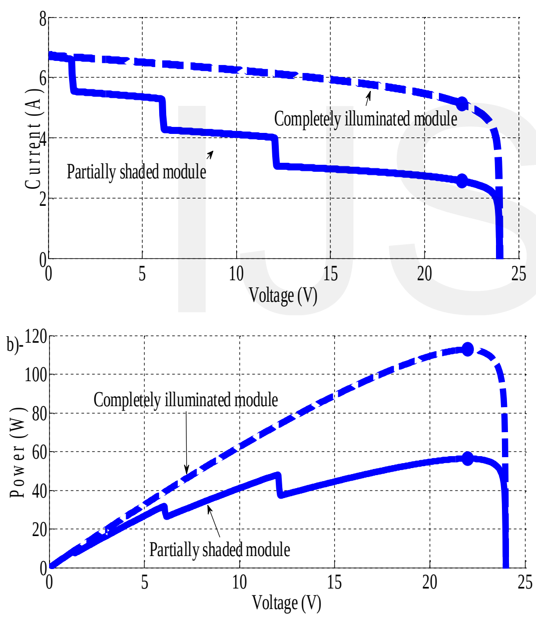

Fig. 20. I-V (a) and P-V (b) characteristic curves for a shaded module in the configuration of figure 19.

This shadow on the module causes power losses of about 50% at MPP. Here, the electrical power losses are higher than those in scenario 5 (27.5%) because one of the strings contains shaded cells in all of its groups. As compared to scenario 2 where the electrical power loss is about 80%, the number of cells and the presence of a blocking diode explains the power reduction in scenario 6.

Scenario 7: Shading rate on 20 PV cells symmetrically distributed in a module with 2 parallel strings

The 20 PV cells of a module are shaded at different rates according to the following shading distributions: the first group of PV cells has 6 shaded PV cells in which 4 are completely shaded and 2 shaded at a rate of 50%; the second group contains 4 shaded PV cells at a rate of 50%; the third group is completely illuminated. These shaded cell distributions are the same for the two strings as shown in Figure 21.

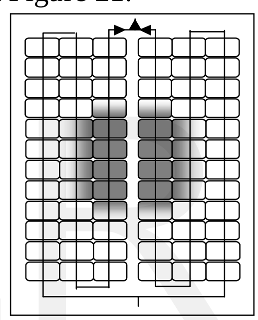

Fig. 21. Shading of 20 PV cells on a 2 stringed module.

The I-V and P-V characteristic curves of this module are given in Figure 22.

For this scenario, the power losses at MPP have been evaluated to be around 60%. The power losses are greater than those of scenario 6 because the shadow casted on a module is not only large in size but also because it shades both strings.

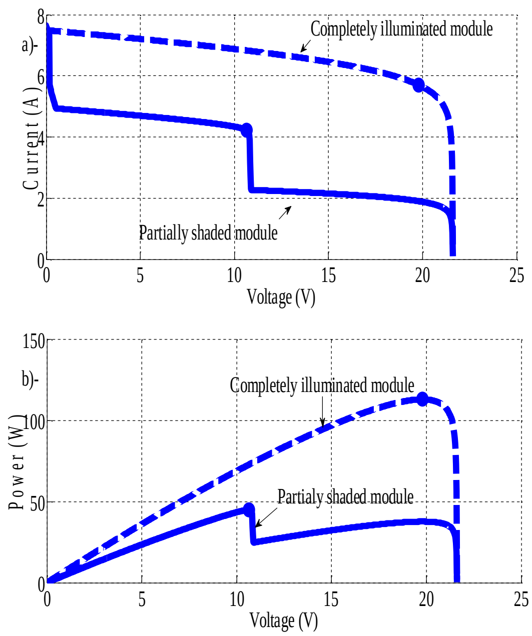

Fig. 22. I-V (a) and P-V (b) characteristic curves for a shaded module in the configuration of figure 21.

4. Conclusion

In this paper, a mathematical modeling and a description of the behavior of a PV module in different scenarios operating under partially shaded conditions are examined. It is observed from this study that a PV module subjected to shading phenomenon, no matter how small it could be, causes a considerable decrease of the power produced even in the presence of protecting diodes that reduce the shading effects. Power losses observed at MPP helped us to notice the aforementioned phenomenon. It is also observed that when a shadow casted on a PV module shades a large number of groups of cells protected by a by-pass diode, the electrical power loss is greater. Likewise, the electrical power loss is less when, less strings are shaded by the shadow casted on a module. This is because the I-V characteristic (or P-V) of a singly shaded PV cell considerably influences that of the whole group, it will thus be advantageous to increase the numbers of groups of cells as well as a mixed electrical interconnection to limit the impact of the shaded cells on the other illuminated cells. Since the losses are significant at the level of a partially shaded module, we plan to extend this study to a photovoltaic array and consider a more dense shadow. Such a study will be helpful to have a better understanding of the shading problem and thus increase the economic efficiency of PV systems, which is the main concern of PV installers.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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