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Experimental Analysis to Extract the Maximum Output of Serial and Parallel PV Module Configurations under Partial Shadow Conditions: A Case Study for Bambey, Senegal

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Abstract

Using an experimental setup, the series configurations (SC) and the parallel configurations (PC) of the PV cell connection are studied to compare their performance under the condition of partial shading s. The performance of the configurations is evaluated by comparing the open-circuit voltage, the short-circuit current, the maximum power point (MPP), the voltage and current corresponding to MPP, and the Fill Factor (FF). The variations of the series resistance and the shunt resistance of a PV module under different irradiance levels are also determined by considering the effect of thermal voltage. Finally, a comparison between the performance losses in the different configurations is presented. The results of this study show that the parallel configuration has the best performance under the conditions of partial shade in the context of this work.

Keywords

PV Cell, Partial Shading, Series Configurations (SC), Parallel Configurations (PC), Fill Factor (FF), Maximum Power Point (MPP)

1. Introduction

Solar energy can be directly converted into electricity using photovoltaic (PV) technology. Currently, solar energy draws worldwide attention and is playing an essential role in providing clean and sustainable energy [1]. Senegal is well-placed to benefit from the successful development of solar energy which depends on the environmental conditions such as the irradiance and the ambient temperature where the modules are deployed, as well as the position and orientation of modules in the field [2] [3]. Less than 40% of the country's rural population benefits from electricity service. This low rate of rural electrification is marked by the problem of extending the grid to remote areas where there are small villages or others with a very dispersed population characterized by its low income and savings [4] [5]. Such a conjuncture suggests the opportunity of a service-based fee model for access to electricity. On the basis of a fee-for-service model, a stand-alone photovoltaic system may be a more appropriate solution to cover the priority needs of lighting and mobile phone battery charge for telecommunications. Also, rural electrification can lead to an increase in agricultural production and allow the rural population to have more income, and to fight against extreme poverty [6] [7]. It is best known that electricity from solar energy is produced by a PV cell that has nonlinear current-voltage (I-V), and power-voltage (P-V) characteristics. The output power of a PV module depends mainly on solar irradiation. To improve the efficiency of the PV module, it must be operated at the MPP [8] [9]. However, the amount of energy production is often influenced by the solar irradiance levels, which are not constant at any time. These variations may be caused by the motion of the sun's position in the sky during the day [10] [11]. As per the energy efficiency concern, partial shading is one of the major causes reducing of the efficiency of PV modules. In partial shading conditions, the cells or the modules of the PV array receive various levels of solar irradiance. The shading causes a mismatch in the electrical characteristics of the panels composing the PV array and results in a significant reduction in the energy yield. The reduction in output is not proportional to the shaded area but depends on the extent of mismatch which in turn depends on other factors like the size of the array, the type of the chosen configuration, the position of the panels in the array, the position and the pattern of shading. Partial shading is caused by several factors such as the neighboring buildings, the trees and/or the passing clouds. Other types of shading are occasionally caused by the installation of the PV system itself. The string of PV modules, the poles, the fences, the link cables, etc. are often sources of shade [12] [13].

The effects of shading on the electrical grids which have specific voltage levels can be very important. They are much higher than the maximum voltage of a single silicon-based PV cell and to interface the PV power generators with the grid, the PV cells are connected in series to form PV modules. The voltage of an individual PV module is normally lower to be conveniently used as a grid-connected PV power generator. Therefore, the generators are built by connecting the PV modules in series and in parallel to get a sufficient voltage level and to increase the nominal power of the generator. The series connection of the PV cells is more affected by unsuitable power loss if the electrical characteristics of the PV cells are not similar or the cells do not operate under uniform conditions. The PV cell with the lowest short-circuit current limits the current of the whole series connection [14]. Under partial shading conditions, for example, if one PV cell of the generator that is composed of series-connected cells is shaded, the short-circuit currents of the non-shaded cells are higher than the series configuration current of the shaded cell. If then the current of the PV power generator is higher than the series configuration current of the shaded cell, the later will be reverse biased due to the other cells in the series connection. In this case, the reverse-biased cell acts as a load in the series connection dissipating part of the power generated by the other cells leading to power loss. This can also lead to hot spots in the shaded cell that can be damaged [15]. The worst situation is when the series connection is short-circuited. Then, the shaded cell dissipates all power generated by the other cells in the series connection. In the literature, various PV array configurations such as series-parallel [9], total cross-tied [16], bridge link [17] and honeycomb [18] are reported. To achieve the required amount of power, the modules in these array configurations are coupled in the series-parallel (SP) combination. Under Partial shading conditions, the mismatch losses occur within the series string of conventional SP combinations leading to electrical characteristics degradations in the PV array.

In this work, we are particularly interested in the effect of partial shading on the energy production of PV modules of the various configurations mentioned above and operating in the environmental conditions of the Bambey area, in Senegal. Two PV modules of 10 Wp each comprising 40 solar cells are studied according to different types of partial shading without bypass diode. Six partial shading scenarios will be treated and discussed and a comparison of the performance losses of the different configurations is then presented. The objective is to select the most appropriate configuration of the photovoltaic field installed in semi-arid climate area zone which provides the best performance, namely the one which presents the lowest losses under the same partial shading conditions.

2. Materials and System Configuration

In this section, the modelling of PV arrays with various topologies and selection of various shading conditions for the PV arrays are described.

2.1. Modelling of the Photovoltaic Cell, the Module and the Array

A solar cell is usually modeled by the electrical diagram presented in **Figure 1**. The PV solar cells are mainly made in semi-conductor devices that convert the solar irradiance into useful electrical energy by the principle of the photoelectric effect. Different types of PV cell models such as the single diode model, two diodes model and three diodes model has proposed in the literature to evaluate the efficiency of the PV cells. In this paper, the single diode PV cell model shown in **Figure 1** is used thanks to a simple approach. The mathematical modelling of the PV cell can be done using Equation (1) expressed as [19]:

$$I_{pv} = I_P - I_D\left[\exp\left(\frac{q\left(V_{pv} + R_s I_{pv}\right)}{AK_B T}\right) - 1\right] - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \tag{1}$$

where I_{pv} is the output current of the cell, I_P is the photo generated current, V_{pv} is the voltage of the cell, R_s is the series resistance, R_{sh} is the shunt resistance and A is the ideality factor. In general, PV cells are connected in series to form a PV module.

The PV array can be formed by connecting the modules in series and in parallel configurations to achieve the desired voltage and the current ratings. Table 1 shows the specifications of the modules used.

2.2. Experimental Setup and Parameters

The experimental setup of 2 × 2 PV array under field conditions is shown in Figure 2. Two PV modules comprising 40 cells of 10 Wp each, a rheostat, two digital multimeters and a 1000 W artificial light source are used in a study. The two modules are connected in parallel (to sum their current) then in series (to sum their voltage), according to the first and second shading studies. The rheostat is used to adjust the intensity of the electric current flowing in a circuit. It consists of a variable resistor sized so as to withstand the maximum intensity of the current that must pass through it. For our case study, the rheostat serves as the loads to be supplied. It measures the maximum current and maximum voltage that our PV modules can generate. The measured output characteristics (I_{sc}, V_{oc}, I_{mp}, V_{mp}, P_{mp}) and the knowledge of electrical parameters such as R_s, R_{sh}, the fill factor (FF), is very important to evaluate the quality and the performance of the modules. The values of these parameters are determined for each module to study how they are affected by changing the scheme of the cell interconnections under uniform irradiance conditions.

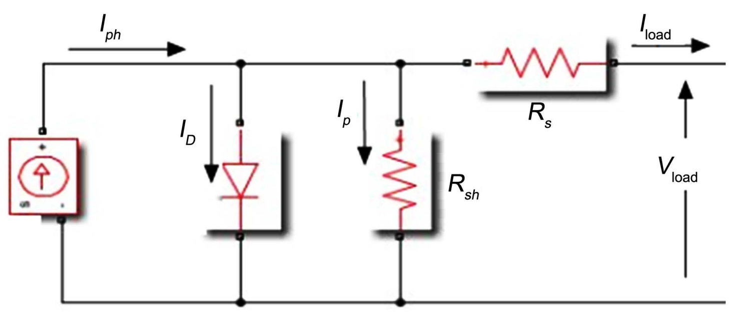


Figure 1. Equivalent circuit of a PV cell.

Table 1. Datasheet characteristics of PV module at STC.

Parameter	Value
Power at MPP (P_M)	10 W
Voltage at MPP (V_M)	21.2 V
Current at MPP (I_M)	0.47 A
Open circuit voltage (V_{OC})	26 V
Short circuit current (I_{SC})	0.51 A

Figure 2. Experimental setup.

3. Shading Patterns Analysis

In order to evaluate the behavior of modules and to choose the optimum cell network which provides the best performance under partial shading conditions, six various partial shading scenarios using different sheets of paper are created, as depicted in Figure 3.

The shading scenarios differ in terms of size and distribution on the modules. The sizes and distributions of the shading patterns used in our study framework are listed as follows:

Test 1: no shading on the modules, it is the reference case;

Test 2: total shading of a cell in one PV module (2.5%);

Test 3: 25% of a row shaded in one PV module on the vertical side;

Test 4: 25% of a row shaded in one PV module on the horizontal side;

Test 5: total shading of a cell in the two PV modules (2.5%);

Test 6: 25% of a row shaded in the two PV modules on the vertical side;

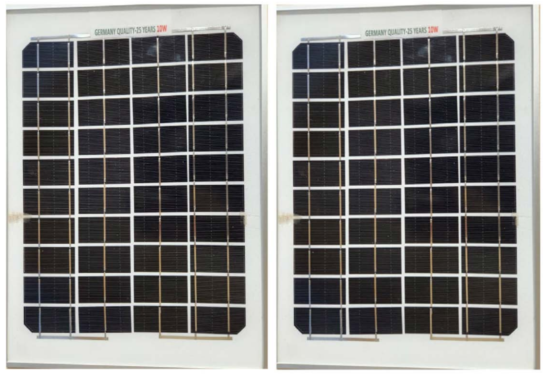
Test 7: 25% of a row shaded in two PV modules on the horizontal side.

4. Performance Parameters of PV Array

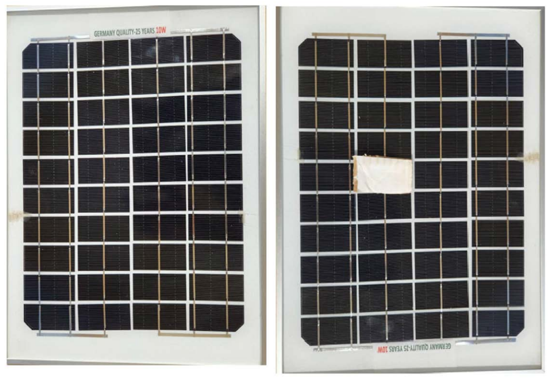
Various parameters such as FF, the performance ratio (power loss), R_S and R_{sh} are considered in the study.

4.1. Fill Factor

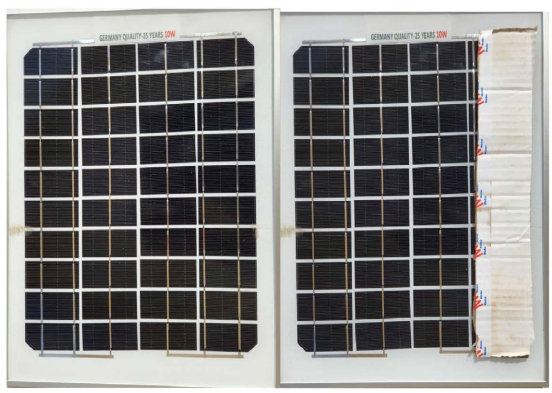
The Fill factor is the measure of the efficiency of PV arrays operating with or without shading conditions and is defined as the ratio between the maximum power generated by the PV array to the maximum rated capacity of the array denoted as:



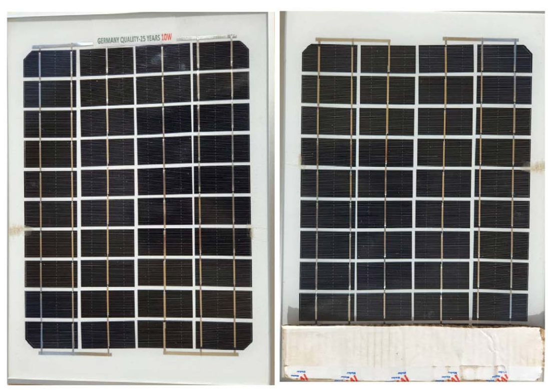
Test 1



Test 2

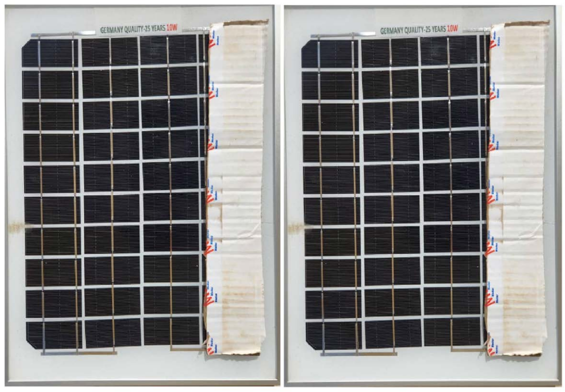


Test 3

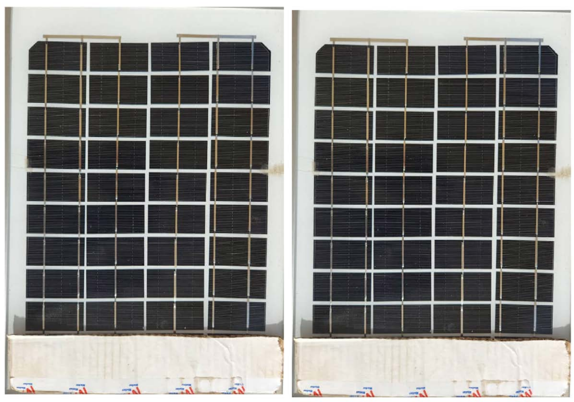


Test 4

Test 5



Test 6



Test 7

Figure 3. Shading patterns.

$$FF = \frac{P_M}{V_{OC} \times I_{SC}} = \frac{V_M \times I_M}{V_{OC} \times I_{SC}}. \quad (2)$$

where P_M is the maximum power, I_M is the maximum current, V_M is the maximum voltage, I_{SC} is the short circuit current and V_{OC} is the open circuit voltage. The value of the fill factor of the PV arrays mainly lies between 0 and 1 values.

4.2. Power Loss

The Power loss in a PV array can be defined as the ratio of the difference in maximum power generated without partial shading and actual maximum power generated during shading. It can be written mathematically as:

$$\Delta P(\%) = \frac{P_{\text{without shading}} - P_{\text{shading}}}{P_{\text{without shading}}} \times 100 \tag{3}$$

4.3. Series and Shunt Resistances

The parameters R_s and R_{sh} are estimated from the slope of the I-V curve near $V = 0$ and $V = V_{oc}$ [20].

$$R_s \approx C_s \frac{V_{OC} - V_M}{I_M} \tag{4}$$

$$R_{sh} \approx C_{sh} \frac{V_{OC}}{I_{SC} - I_M} \tag{5}$$

C_s and C_{sh} are empirically determined for each technology type. The values of coefficient $C_s = 0.34$ and $C_{sh} = 5.36$ for multicrystalline Si [20].

5. Results and Discussion

The effect of partial shading effects is very important for a PV system and even a low level of shading can negatively affect the performances [21]. During the shading effects, without the bypass diodes, the modules receiving low illumination cannot activate to the bypass the additional current generated by the unshaded modules.

This situation results in the formation of multiple peaks in the characteristic curves of the system. The effect of partial shading effects in two solar PV modules in parallel configuration and series configuration without the bypass diodes is investigated. **Figure 4** and **Figure 5** show the characteristic curves of the two photovoltaic generators in parallel configuration and series in configuration without the bypass diodes operating under the cases of partial, shading effects respectively.

If one or more non-identical cells are introduced into a parallel connection, the lowest voltage generated by the cells will be imposed on all of the other cells and the output current will be the sum of the currents under the same conditions. This is what is seen at the level of these two characteristic curves in **Figure 4**. Here we noticed that it is the intensity of the resulting current (on I-V characteristic curves) and the power (on P-V characteristic curves) that are more affected by shading than the resulting voltage. One inflection point was noted at the I-V characteristic curves and two inflection points as shown by **Tests 2** and **5**, respectively; which alludes to the presence of partial shading on a single module of the two. When 25% of the surface of one of the two modules is affected by the shading, the intensity of the current and the power are halved and the voltage always remains the same. So, it can be deduced that the shaded module is no longer producing. Hence, basing to **Tests 6** and **7**, it is noted that if both modules are affected by this same percentage of shading, the production of both modules is almost zero. So, the two modules are totally degraded.

If one or more non-identical cells are introduced into a series connection, the lowest current generated by the cells will be imposed on all of the other cells and

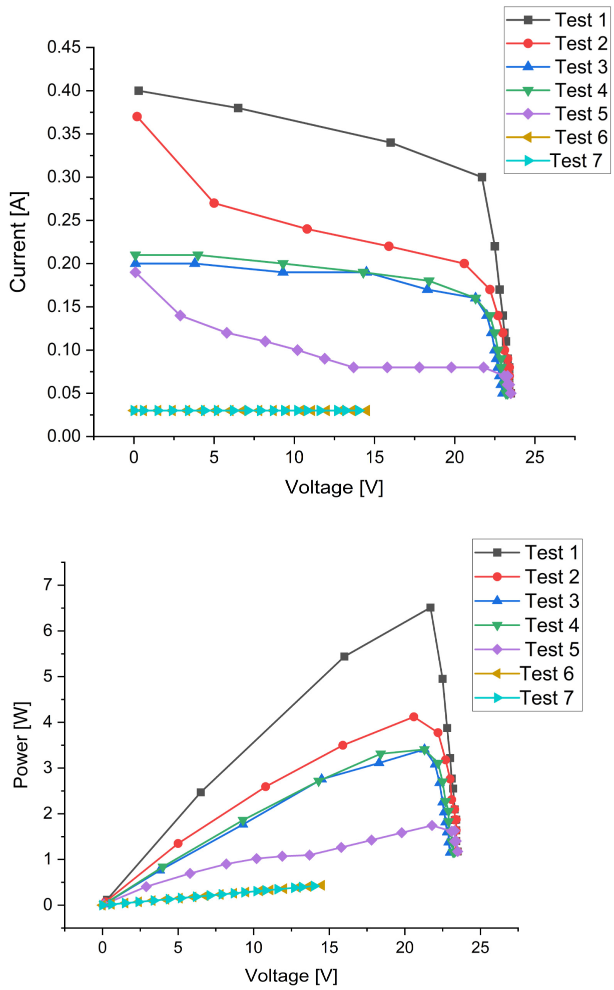


Figure 4. I-V and P-V characteristics for parallel configuration of the PV modules: Without shading (**Test 1**) and with shading (**Tests 2**-**7**).

the output voltage will be the sum of the voltages under the same conditions. So, the resulting voltage is more affected relatively to the strength of the resulting current. The observation in the characteristic curves I-V and P-V of **Figure 5**, **Tests 2**, **3** and **4** show that the value of the voltage decreased with the shading but the intensity of the current is almost constant. The same is true for the power at the level of the P-V characteristic curves. This is because only one module is affected by the shading and as in a series configuration the current is the same and the voltage can be summed. So, the unshaded module will produce the resulting current and the resulting voltage which is the sum of the voltages of the two modules and will be disturbed by the shading effect. It was found during the test that, the current intensity was almost halved; which can be explained by the fact that both modules are weakly affected by shading effects, therefore both modules will see their intensities and their tensions affected. Furthermore, it can be remarked that, using the results of **Tests 6** and **7**, if this amount of shading is removed enough, the two modules being totally degraded because of the shading no longer produce.

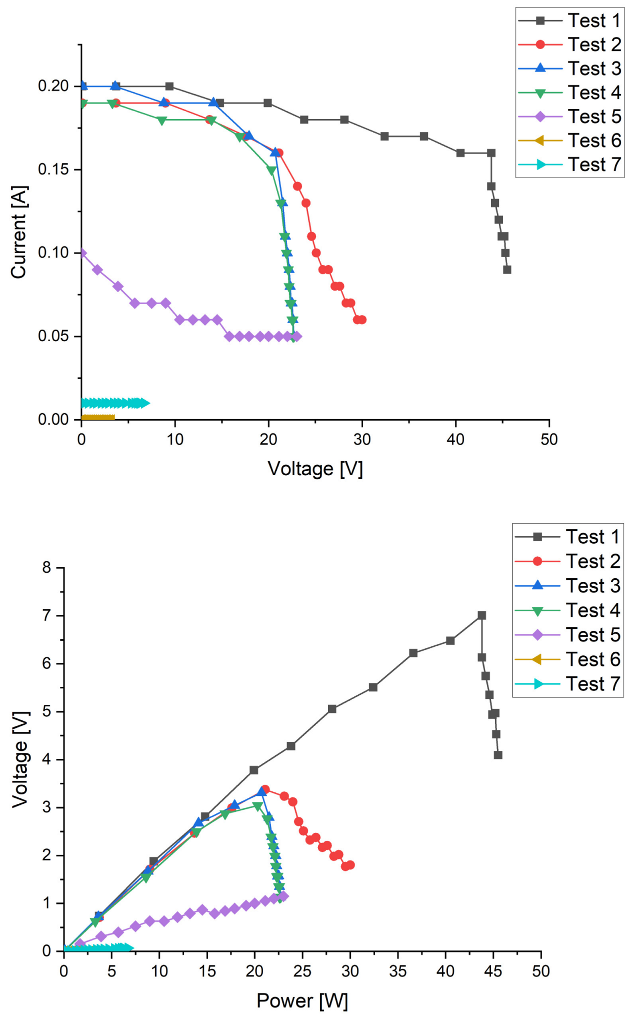


Figure 5. I-V and P-V characteristics for serie configuration of the PV modules: without shading (**Test 1**) and with shading (**Tests 2-7**).

The resultant values are tabulated in **Table 2**. This suggests a series of observations and conclusions:

❖ Short Circuit Current:

Figure 4 shows that, the short-circuit current decreases with the decrease of the illuminated zone of the cell corresponding to the increase of the shading rate, due to the input of the shading of the different areas. For the parallel and series arrangements of the two PV modules, it is shown that the I_{sc} decreases from 0.4 A to 0.03 A and from 0.2 A to 0.01 A, respectively. So, it underwent a reduction of about 92.5% and 95%, respectively, from its initial value. These decreases correspond to the input of a shading effects whose area represents almost 25% of the total surface of the module and as a function of the position of the shading. Consequently, the module current would be directly influenced by the increase of the shading effects rate. As the module in question is composed of solar cells in series, it operates at the same current (branch current), which leads to the reverse polarization of the shaded cell which dissipates energy generated by the

Table 2. PV array configurations of performance parameters under different shading conditions.

	Parameters	Shading conditions						
		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
PC	P_m (W)	6.510	4.120	3.408	3.408	1.744	0.435	0.420
	I_{sc} (A)	0.400	0.370	0.200	0.210	0.190	0.030	0.030
	V_{oc} (V)	23.50	23.50	23.00	23.30	23.50	14.50	14.00
	I_{mp} (A)	0.300	0.200	0.160	0.160	0.080	0,030	0.030
	V_{mp} (V)	21.70	20.60	21.30	21.30	21.80	14.50	14.00
	FF	0.693	0.474	0.741	0.696	0.391	-	-
	ΔP_m (%)	0	36.71	47.65	47.65	73.21	93.32	93.55
	ΔI_{sc} (%)	0	7.500	50.00	47.70	52.50	92.50	92.50
	ΔV_{oc} (%)	0	0	2.130	0.850	0	38.30	40.42
	ΔI_{mp} (%)	0	3.300	46.67	46.67	73.33	90.00	90.00
	ΔV_{mp} (%)	0	5.070	1.840	1.840	−0.460	33.18	35.48
	ΔFF (%)	0	21.9	-	-	43.34	-	-
	R_s (Ω)	1.920	4.640	3.400	4	6.800	0	0
	R_{sh} (Ω)	1259.60	740.94	3082	2497.76	1445.09	-	-
SC	P_m (W)	7.008	3.376	3.312	3.045	1.150	0	0.067
	I_{sc} (A)	0.200	0.190	0.200	0.190	0.100	0	0.010
	V_{oc} (V)	45.50	30.00	22.70	22.70	23.00	3.200	6.700
	I_{mp} (A)	0.160	0.160	0.160	0.150	0.050	0	0.010
	V_{mp} (V)	43.80	21.10	20.70	20.30	23.00	3.200	6.700
	FF	0.770	0.592	0.730	0.706	0.500	-	-
	ΔP_m (%)	0	51.83	52.74	56.55	83.59	100.0	99.04
	ΔI_{sc} (%)	0	5	0	5	50.00	100.0	95.00
	ΔV_{oc} (%)	0	34.07	50.11	50.11	49.45	92.97	85.28
	ΔI_{mp} (%)	0	0	0	6.25	68.75	100.0	93.75
	ΔV_{mp} (%)	0	51.83	45.89	53.65	47.89	92.69	84.70
	ΔFF (%)	0	23.12	5.19	8.31	35.07	-	-
	R_s (Ω)	3.400	17.80	4	5.12	-	-	-
	R_{sh} (Ω)	6097	5370	3041.80	3041.80	2465.60	-	-

other illuminated cells. The slope of the deformations underwent by the I-V characteristics gives information on the short circuit currents.

❖ Open Circuit Voltage:

From **Figure 4**, we also noted the dependence of Voc on the position and on the shading rate for the series and parallel configurations of the modules. It can be seen that with more shading, the voltage decreases because the illuminated part is derived by the shaded part. Thus, the shaded solar cell is considered as a shunt resistance connected to the active part of the module. The voltage decreases from 23.5 V to 14 V when the modules are connected in parallel and from 45.5 V to 6.7 V when they are connected series, corresponding to reduction rates of approximately 40.4% and 85.3%, respectively.

❖ Maximum Power:

Figure 4 also unmasks the trend of the maximum power as a function of the position and the shading effects rate. It can be noticed that the MPP decreases with the increase of shading on PV modules. The MPP underwent a reduction of 93.55% and 99.04% according to the two types of parallel and series configurations, respectively. These losses in power would be dissipated into the form of heat in the shaded part of the PV modules, just where the cells are shaded. This effect should be considered, when the system is connected to a maximum power point tracking (MPPT) inverter, as it may cause improper exploitation of the photovoltaic system. The search for the maximum power point becomes problematic for the MPPT with the presence of inflection points on the I-V and P-V curves. Whatever point is identified at level, it cannot correspond to the actual maximum power point of the unshaded panel and it will always be of smaller value, which will inevitably decrease the overall output of the system.

❖ Fill Factor, Series and Parallel Resistances:

On the one hand, it is obvious that the fill factor decreases with the increase in shading rate. This decrease is mainly due to the decrease of $V_{mp} \times I_{mp}$ which represents the values of the operating voltage and current at the maximum power and the term $V_{oc} \times I_{sc}$. On the other hand, the series resistance (R_s) which is the internal resistance of the cell depends mainly on the resistance of the used semiconductor, the contact resistance of the collector gates and the resistivity of these gates. But in this case study, the latter underwent an increase as soon as there is shading. And this increase is quite large in the case of the serial configuration. As for the shunt or parallel resistance (R_{sh}), corresponding to the leakage current in the p-n junction, it has undergone a reduction as soon as there is shading. This reduction is noted on all the tests when the two modules are in the series configuration. Because after the maximum current deviates from the short-circuit current and the voltage is almost the same. However, for better functioning of the PV solar system, the ideal for these resistors is to have a series resistance which tends toward zero and a shunt resistance which tends toward infinity. Therefore, the shading effects contribute to decreasing the R_{sh} and increasing the R_s which leads to the causes of degraded performance of PV modules.

6. Conclusions

Many factors determine the ideal output or optimum yield in a photovoltaic module. The environment is one of the contributing factors which directly affect photovoltaic (PV) module performance. The performance investigation of two PV modules in series and parallel configurations is carried out by means of experimental studies. We have also presented and compared the performance of all these PV configurations in the case of six forms of partial shading. The performance parameters such as the power, the current and the voltage, the power losses and the fill factor are considered to analyze the performance under the considered shading patterns. The salient points of the comprehensive study can be stated here as:

- The level of the degradation of the module depends on the shading not only on the size of the shading pattern, but also it depends on the type of the configuration between the PV modules;
- For the same shading effects rates and patterns, the series configuration of the PV modules generates much more losses than the parallels configuration;
- The power loss in parallel configuration turns out to be much lower, namely 36.71% against 51.83% for the series configuration (case of the shading pattern of **Test 2**). Moreover, the power loss in parallel configuration is also observed to have a maximum magnitude of 93.55%, as compared to 100% for SC (case of shading of **Test 7**);
- In a parallel configuration, the FF has as the maximum value of 0.741, which is more than 0.730 in series configuration (case of shading pattern of **Test 3**). But for the other cases of shading, the FF in serial configuration is always superior to the one in the case of parallel configuration.

The results obtained in this work could be used in an intelligent algorithm for tracking the overall maximum power point in the case of partial shading.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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