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An Experimental Investigation on Photovoltaic Array Power Output Affected by the Different Partial Shading Conditions

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Abstract: This paper presents an experimental investigation on photovoltaic array (PV array) power output affected by partial shading conditions (PSCs). An experiment setup of a PV array with a series configuration using 2 × 4 photovoltaic modules (PV modules) was built. The power output loss due to the shading effect on the first photovoltaic cells (PV cell) connected with bypass diodes of each photovoltaic module, installed in the PV array in the horizontal direction, was evaluated. Depending on the direction of the sun relative to the PV array configuration, the shading percentage was measured during the test and recorded the current and voltage of the PV array. The performance evaluation of the PV array configurations is referred to with respect to the values of maximum power voltage, the maximum power current, maximum power output, power output losses and fill factor (FF). The experimental results show that 44% shading of the first PV cells affects PV array power output loss by more than 80%.

Keywords: photovoltaic (PV) module; shading; power output loss; partial shading conditions (PSCs); PV array configuration

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1. Introduction

The photovoltaic (PV) power generation system is an attractive technology among solar irradiance converting options. By 2035, the power from PV power generation systems will increase to over 26 times that in 2010 [1]. Since the fundamental role of the photovoltaic (PV) cell is to absorb as much incoming solar irradiance as possible, the PV cell should always be unshaded and uncovered to avoid power output loss. Thus, a shaded PV cell or PV modules that negatively affect the PV power generation system are a crucial issue and emerging research topic. The number of research studies on the effects of shading on PV cells and PV modules to maximize the amount of solar irradiance to be absorbed by a PV cell has increased considerably [2].

In general, a PV array consists of a linked PV module that is composed of individual PV cells [3]. Under shading conditions, some PV cells or PV modules in a PV array are shaded due to trees, clouds, close buildings, or any other objects that appear close to the PV cell or PV module. In the case of shading, a PV array produces power losses, and the power generation decreases [4]. Moreover, to avoid shading that may cause power output reduction, an appropriate PV module installation, together with layout measurement and design, should be considered. Specifically, there should be a space between the PV modules, which is calculated based on the location and PV module dimensions to prevent shading [5].

Other studies have presented and developed a mathematical model [6,7] of single or two-diode PV modules using simulation software, such as MATLAB-Simulink [8] and Power System CAD [9], or LT-Spice [10], to study and analyze the effects of shading under uniform and nonuniform irradiation and different temperature levels [11–13]. However, since it is challenging to predict shadow patterns and simulate them using software, a simulation approach does not seem feasible for the actual scenarios. Other relevant studies in the literature focus on the performance of PV modules affected by shadows, which can occur due to various reasons, e.g., trees, clouds, close buildings, or any other objects that appear close to the PV module.

The study in [14] used a PV module with 60 cells (six cells in width and ten cells in length), and the performance under different shadow transmittance was investigated. The results showed that the shadow moved one PV cell length during every half-hour period and took three hours to reach the last cell's end when the shadow moved horizontally. The author found that shadow on the PV module's second cell caused more power output loss. Dolara et al. researched the vertical and horizontal shading effect on PV modules and found that vertical and horizontal shading reduced the PV module power output. The results show that the PV module power output decreased notably by 70% for the 50% horizontal shading effect due to the PV cell series connection [15].

Rabanal-Arabach et al. found that, as the sun altitude increased, a PV module's frame introduced significant shading, which had a critical effect on the daily output power of the vertical installation of a bifacial module. It was shown that the mounting frame shading effect decreased power output by about 10%. At 10:00 a.m., the PV module's frame introduced shading, and about 75% of the first PV cell in the first vertical column was shaded [16]. Zhu et al. conducted an experiment using a frameless bifacial PV module, which produces electricity from both the front and back sides. The bifacial PV module requires system holders and frames for its installation, introducing shading on the PV module. The frame height is an important factor for the PV module since it could introduce shadow that affects the power output [17].

Since partially shading only one PV module in the PV array must be verified to demonstrate whether PV array power output could be reduced, this paper aims to investigate the PV module's shading effect in PV array power output.

The experimental results show that 44% shading of the first PV cells affects PV array power output loss by more than 80%. It is seen from the results that, in the case of the series configuration of a PV array, even if only one PV module fails to generate electricity due to the event of any failure or partial shading, the total amount of power generation of the whole PV array is reduced.

The contributions of this work are as follows:

1. The literature so far focuses on shading due to trees, clouds, close buildings, or any other objects that appear close to a PV module. In this research, an experimental setup of a PV array with series configuration using 2×4 PV modules was built.
2. Depending on the sun's direction relative to the PV module installation, and due to the metallic frame close to the PV array, different PSCs with different percentages were recorded at 30-min intervals from 8:30–11:00 a.m. The power output loss due to the shading effect was evaluated and compared with the PV array at the same time and under the same conditions.
3. The current and voltage values of the PV array were obtained. The performance evaluation of the PV array configurations is referred to with respect to the values of maximum power voltage, maximum power current, maximum power output, power output losses, and fill factor (FF).

This paper is organized as follows. Section 2 describes the method used experimentally to investigate the effects of PSCs on a PV array configuration. Section 3 presents the results of PSCs on PV array configuration. Section 4 presents the evaluation results of PSCs on PV array power output loss and fill factor. The final section presents concluding remarks and ideas for possible future work.

2. Experimental Setup

2.1. The PV Module Configuration and I-V Characteristics

A fundamental understanding of PV module configuration is essential in investigating the effects of shading on PV module power output. The current flow of a typical poly-crystalline silicon PV module is shown in Figure 1. In general, the PV module was lined with several PV cells of about 150 by 150 mm. The PV module is divided into three submodule blocks with 24 PV cells in each. All the PV cells were electrically connected in series. The plus and minus of each PV cell were connected one after another. All the PV cells would be affected if only one PV cell failed to generate electricity due to the event of failure or complete shading [18]. To manage this situation, actual PV modules use an electric device called a bypass diode attached at the backside and that is divided into several submodule blocks to divert and provide an alternative route for the current around PV cells unable to conduct in line with others. Using a bypass diode, the failure submodule can be bypassed, and the impact can be reduced. Even if only one of the 72 PV cells is shaded, only one submodule block is completely separated. The total amount of the 20 PV cells power generation is reduced by about 33%.

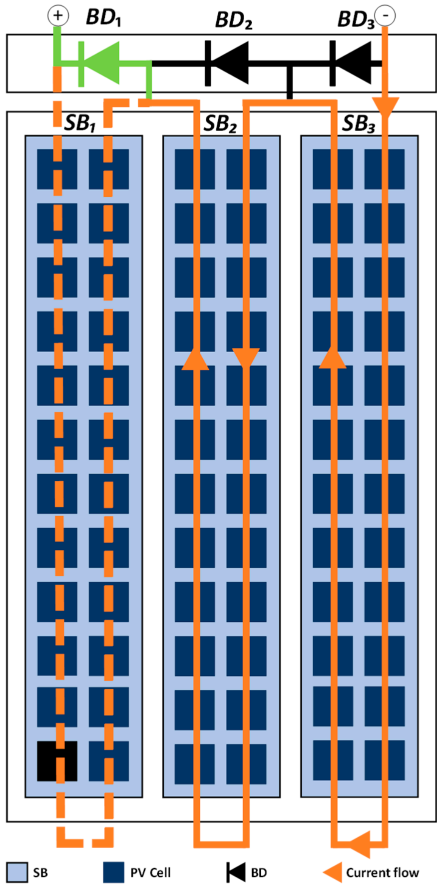


Figure 1. PV module configuration under in study showing 72 PV cells connected in three submodules, namely: SB_1, SB_2, and SB_3, and three bypass diodes, namely BD_1, BD_2, and BD_3. If only one PV cell (lower left corner) is fully shaded and stops generating electricity, no current will flow through that PV cell, resulting in zero power output for submodule block SB_1. Electricity then flows through bypass diode BD_1, disconnecting the entire submodule block SB_1, including the shaded PV cell, from the electricity flow.

In a typical investigation, the following four points are necessary to investigate PV cell or PV module characteristics. The open-circuit voltage (V_{oc}) is the voltage available from the PV module when the current is zero. The short circuit current (I_{sc}) is the current through the PV module when the voltage across the PV module is zero. The maximum power voltage (V_{mp}) is the voltage when the power output is the highest, which is the actual voltage when the PV module is connected to a load. The maximum power current (I_{mp}) is current when the power output is greatest, which is the actual current when the PV module is connected to a load. The current across the PV cell depends on many different factors; for example, the number of sunlight photons that come from solar irradiation to be converted to direct current (DC) electricity. The current depends on the PV cell's total area [19], while the voltage depends on the outside temperature and that of the PV cell itself [20].

The (V_{oc}) and (I_{sc}) can be obtained from a PV module during the no-load period. However, as (V_{oc}) remains almost the same under normal operations, it is impossible to diagnose the (abnormal) performance of a PV module by measuring the values of (V_{oc}) and (I_{sc}). Therefore, the main goal of this research is to measure the values of (I_{mp}) and (V_{mp}) so that the value of the actual maximum power output (P_{mp}) can be obtained using Equation (1):

$$P_{mp} = I_{mp} \times V_{mp} \tag{1}$$

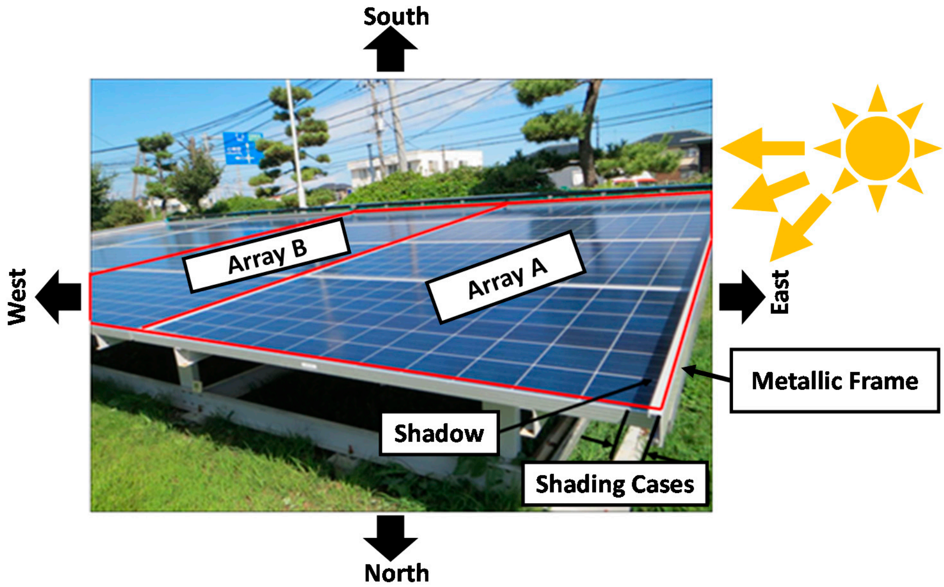
2.2. The PV Array Configuration and Load Profile

In a PV system, there are different PV array configurations to extract more power output and improve efficiency under PSCs. The series and parallel configurations are considered simple and basic configurations. In addition, an alternative PV array configuration is proposed, such as a total-cross-tied (TCT) configuration, bridge-link (BL) configuration, and honey-comp (HC) configuration [3,21–23]. In this experiment, the series configuration on the PV array was carried out.

The experimental setup is shown in Figure 2 and consists of two sets of PV arrays, namely: array A and array B. PV array A included four PV modules installed horizontally and connected in series with eight bulbs connected in parallel. PV array A was affected by PSCs. The four PV modules' surface areas of array A were horizontally shaded due to the metallic frame close to the PV array (Figure 2). PV array B also consisted of four PV modules installed horizontally and connected in series with eight bulbs connected in parallel. Array B was not affected by PSCs. All the PV modules faced south. A Jinko JKM310P PV module was used for this experiment. The specifications of the PV module under standard test conditions (STC) of 1000 W/m^2 solar irradiation, 1.5 air mass, and 25 °C cell temperature are provided in Table 1. The experiment was conducted on 2 October, 2019, from 8:00 to 11:00 a.m., as Daiichi Kasei Co., Ltd., a factory in Tochigi Prefecture, Japan. The experiment was limited from 8:30 a.m. to 11:00 a.m. instead of being conducted during the daylight hours from sunrise to sunset, including low direct normal irradiance hours to discover the shading effect at its maximum extensions during this period. The solar radiation level in the early morning hours preceding the experiment period was minimal. After the experiment time, the sun begins perpendicular to the Earth's surface, and the radiation level begins to diminish until the shadow disappears. In this research, the parallel experiments were not performed as the experiment required exact weather conditions in terms of temperature, cloudiness, humidity, and irradiance level. It is not easy to guarantee the same weather conditions during experiment days since weather conditions vary from one day to another.

Table 1. Specification of the PV module.

Item	Info
Manufacturer	Jinko Solar
Model no.	JKM310P
No. of cells	72 (6 × 12)
Cell material	Poly-crystalline
Cell dimension	156 × 156 mm
Open circuit voltage (V_{oc})	45.9 V
Short circuit current (I_{sc})	8.96 A
Maximum power current (I_{mp})	8.38 A
Maximum power voltage (V_{mp})	37.0 V
Maximum power (P_{max})	310 W



(**a**)

(**b**)

Figure 2. The experimental setup. (**a**) A shadow was introduced on the first PV cells connected with bypass diodes of the PV modules in array A due to the metallic frame and (**b**) eight bulbs connected in parallel.

Four PV modules (310 W/module) were connected in series for each array to conduct the experiment, as mentioned. The total expected power output was 1240 W. Additionally, eight light bulbs (200 V, 180 W) were connected in parallel as a load for each array (A and B), as shown in Figure 3. In this experiment, light bulbs were used because they always shine, irrespective of their type of connection (direct or alternating current), i.e., the bulbs can shine no matter how the current flows. The values of (I_{mp}) and (V_{mp}) were measured. A Hioki cm4371 multimeter was used to measure the array current (I_{mp}), and a Sanwa digital multimeter pm3 was used to measure the array voltage (V_{mp}). The voltage and current values for array A and array B were recorded simultaneously to minimize the instant change effect in the irradiance level every 30 min. The PV arrays were directly connected to the load, i.e., the PV modules did not operate at the maximum power level because of the experiment instrument's limitations. The PV module temperature was measured using a digital thermometer (TPM-10), and the humidity was measured using a testo 625 thermohygrometer (Table 2). Figure 4 shows the partial shading conditions of PV modules. Figure 5 shows the monthly average solar irradiation [24] and monthly minimum, maximum, and average temperature of the experiment location [25].

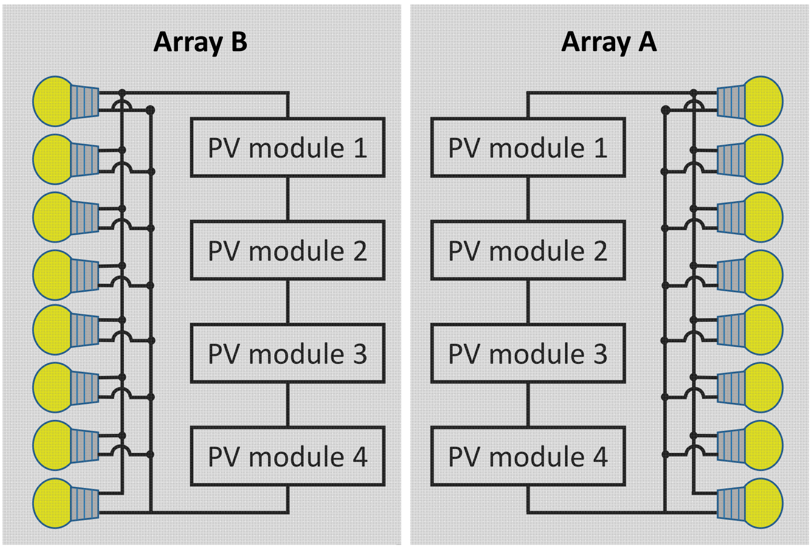


Figure 3. PV array in a series configuration and the load profile.

Table 2. Measured values during the experiment.

Time	Outside Temp (°C)	Humidity (%)	Module Temp (°C)
8:30	23.9	50	38.8
9:00	27.9	43	45.1
9:30	28.3	31	46.2
10:00	30.8	30	53.7
10:30	32.1	33	53.7
11:00	32.9	31	58.1

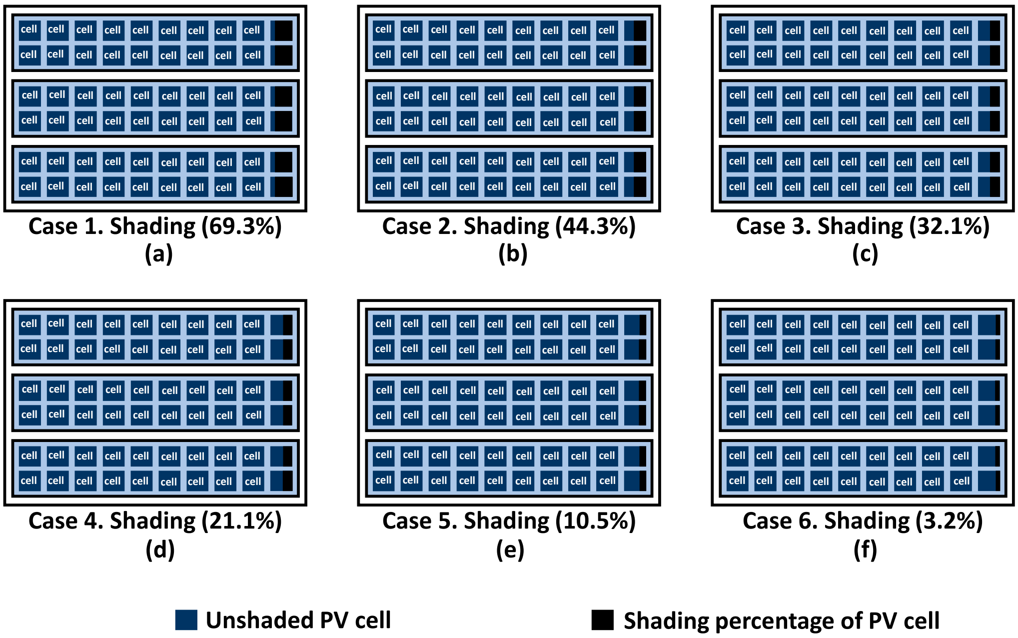
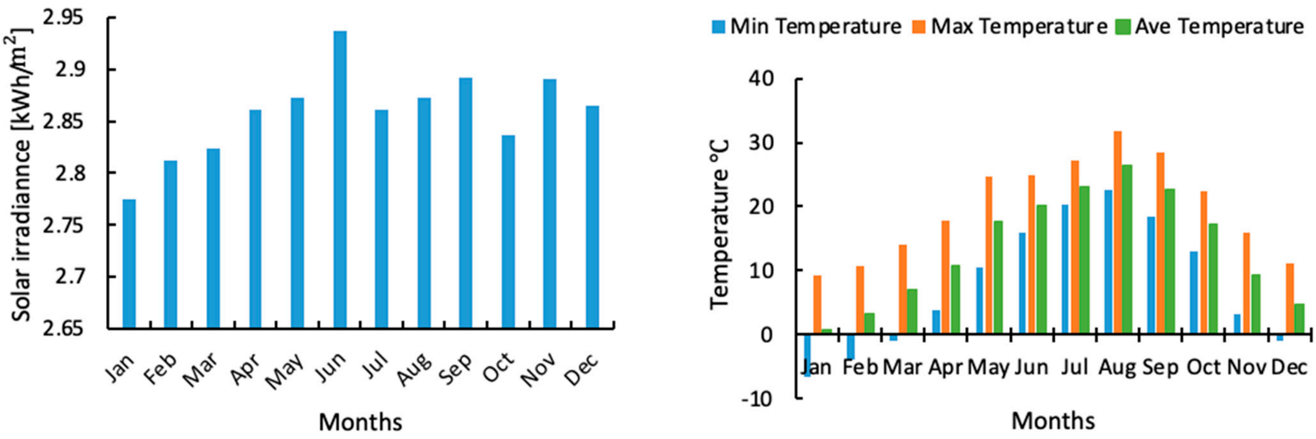


Figure 4. Partial shading conditions of PV modules in the PV array A configuration. (**a**) Case 1, (**b**) case 2, (**c**) case 3, (**d**) case 4, (**e**) case 5, and (**f**) case 6.



(**a**) (**b**)

Figure 5. (**a**) Monthly average solar irradiation and (**b**) monthly minimum, maximum, and average temperature [25] of the experiment location.

2.3. Partial Shading Conditions (PSCs)

Depending on the sun's direction relative to the PV array configuration, the shading percentage was measured during the test. This subsection describes the six different cases of PSCs on a 1 × 4 PV array (array A) configuration to investigate the shading effect on the first PV cells connected with the bypass diode of the PV modules, which described as follows:

Case 1: Under this PCSs case, the first PV cell in each PV module in the array A configuration is shaded. The shading percentage covering the PV cell was 69.3% at 8:30 a.m., as shown in Figure 4a.

Case 2: Under this PCSs case, the first PV cell in each PV module in the array A configuration is shaded. The shading percentage covering the PV cell was 44.3% at 9:00 a.m., as shown in Figure 4b.

Case 3: Under this PCSs case, the first PV cell in each PV module in the array A configuration is shaded. The shading percentage covering the PV cell was 32.1% at 9:30 a.m., as shown in Figure 4c.

Case 4: Under this PCSs case, the first PV cell in each PV module in the array A configuration is shaded. The shading percentage covering the PV cell was 21.1% at 10:00 a.m., as shown in Figure 4d.

Case 5: Under this PCSs case, the first PV cell in each PV module in the array A configuration is shaded. The shading percentage covering the PV cell was 10.5% at 10:30 a.m., as shown in Figure 4e.

Case 6: Under this PCSs case, the first PV cell in each PV module in the array A configuration is shaded. The shading percentage covering the PV cell was 3.2% at 11:00 a.m., as shown in Figure 4f.

2.4. Uncertainty Analysis

The uncertainty of a derived parameter, X, due to the uncertainty in the individual measured variables, $x_1, x_2 \ldots x_n$, is referred to as uncertainty propagation. The general form of the total uncertainty in derived parameter X can be calculated using the following expression [26].

$$\omega_x = \sqrt{\left(\frac{\partial X}{\partial x_1}\right)^2 {\omega_{x_1}}^2 + \left(\frac{\partial X}{\partial x_2}\right)^2 {\omega_{x_2}}^2 + \ldots + \left(\frac{\partial X}{\partial x_n}\right)^2 {\omega_{x_n}}^2} \quad (2)$$

where ω_x is the uncertainty of the variable x, ω_{x_n} is the uncertainty of parameter x_n, and $\partial X/\partial x_1$ is the partial derivative of X with respect to x_1. The maximum uncertainties in the different measured and evaluated parameters obtained from an experimental error analysis are presented in Table 3. Based on Equation (2), the maximum calculated uncertainty in the power output in array A is ±46.25 W, and the maximum calculated uncertainty in the power output in array B is ±46.5 W.

Table 3. Accuracy of the measuring devices.

Parameters	Accuracy
Current, (A)	±1.3%
Voltage, (V)	±0.7%
Humidity	±2.5%
PV module temperature, (°C)	±1

3. Experimental Results of PSCs

3.1. The Effect of PSCs on PV Array Configuration

This section presents experimental result regarding the shading effect on PV array power output. Table 4 summarizes the recorded values for the voltage (V_{mp}) and the current (I_{mp}) with shading (array A) and without shading (array B).

Table 4. Electrical results of PV arrays with and without shading.

Case	Time	Array A with Shading (4 PV Modules)				Array B without Shading (4 PV Modules)		
		Shading Percentage [%]	V_{mp} [V]	I_{mp} [A]	P_{mp} [W]	V_{mp} [V]	I_{mp} [A]	P_{mp} [W]
Case 1	8:30	69.3	9.51	1.72	16.36	113.3	4.63	524.5
Case 2	9:00	44.3	42.6	2.95	129.2	139.5	5.21	726.8
Case 3	9:30	32.1	86.7	4.06	352.0	140.8	5.23	736.3
Case 4	10:00	21.1	129.3	4.98	643.9	143.4	5.23	749.9
Case 5	10:30	10.5	142.5	5.18	738.1	142.6	5.19	740.0
Case 6	11:00	3.2	140.9	5.20	732.6	143.4	5.20	745.8

The shading effect was recorded at 30-min intervals, from 8:30–11:00 a.m. The PV modules in arrays A and B are connected in series; therefore, the voltage is equal to the sum of a single PV module in each array. The current remains uniform across each array. The comparison of array A and array B is shown in Figure 6. At 8:30 a.m., in the case of array B with no shading effect, the voltage (V_{mp}) was increased to 113.3 V. The current (I_{mp}) and power output (P_{mp}) were 4.63 A and 524.5 W. At 11:00 a.m., the voltage (V_{mp}), current (I_{mp}), and power output (P_{mp}) were 143.4 V, 5.20 A, and 745.8 W. For array A, the array was affected by shading at 8:30 a.m. and the voltage (V_{mp}) and current (I_{mp}) dropped to 9.51 V, 1.72 A. The total output power (P_{mp}) of array A also decreased to 16.36 W.

The effect of shading percentage on the first PV cells connected with a bypass diode of the PV modules in array A is shown in Figure 7. The shading percentage changes corresponding to the direction of the sun from 8:30 to 11:00 a.m. The shading percentage reduces dramatically during this period. When the shading percentage on PV array A increased, the voltage (V_{mp}), current (I_{mp}), and power output (P_{mp}) drops dramatically. It could be recognized that array A power output was inversely proportional to the shading percentage.

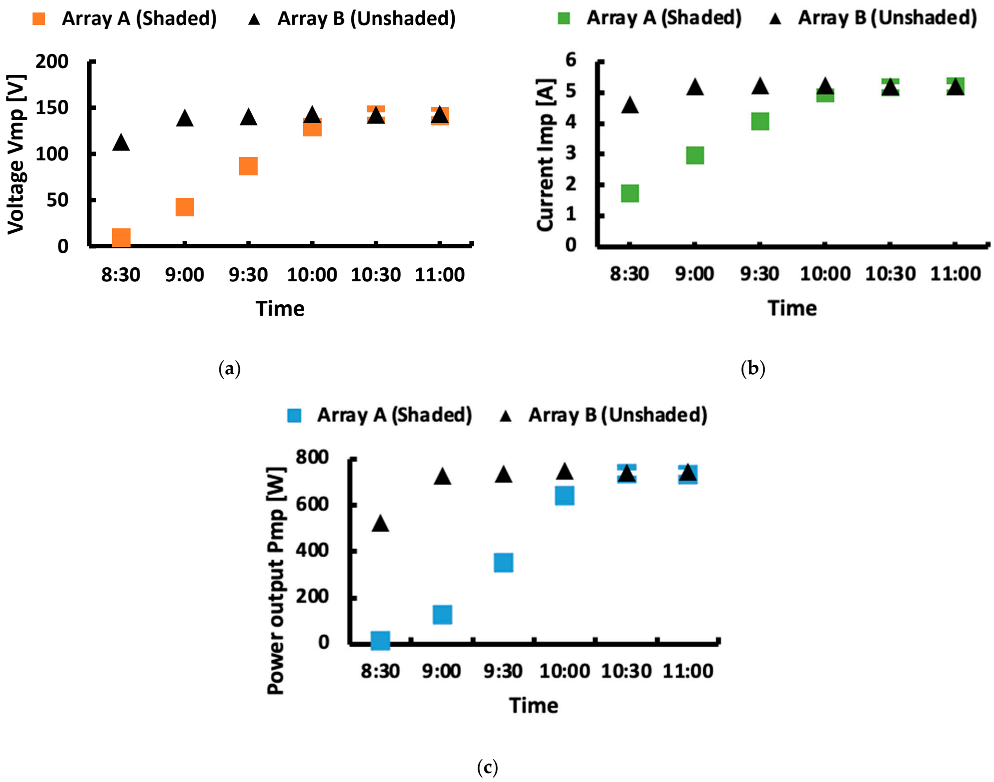


Figure 6. Comparison between array A and array B: (**a**) voltage and time, (**b**) current and time, and (**c**) power output and time.

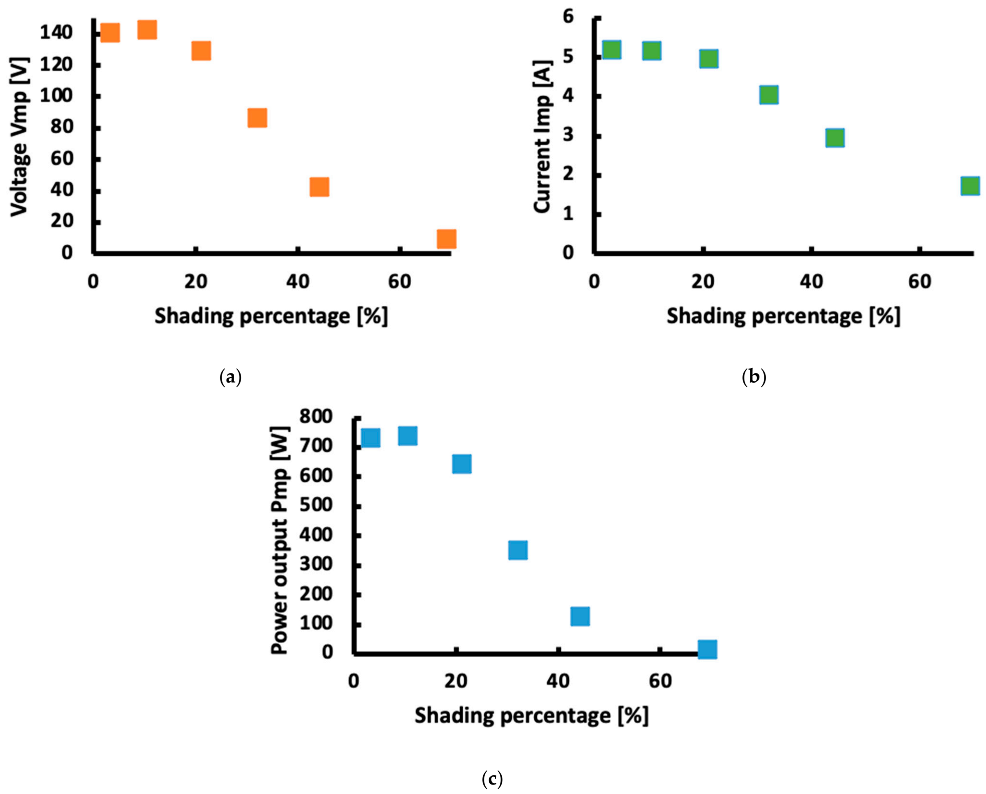


Figure 7. The effect of shading percentage on the first PV cells connected with bypass diode of the PV modules in array A: (**a**) voltage and shading percentage, (**b**) current and shading percentage, and (**c**) power output and shading percentage.

3.2. The Effect of PSCs on PV Module Temperature

The effect of six different PSCs on the PV array A module temperature is shown in Figure 8. The increase in the shading percentage on the PV cells decreased the temperature of the PV module. This result agrees well with that obtained in [11]. It can be observed from the results that a high shading percentage significantly affected the PV module temperature. The increase in shading percentage decreases the PV module temperature. In case 1, when the shading percentage was about 70%, the PV module temperature was about 40 °C.

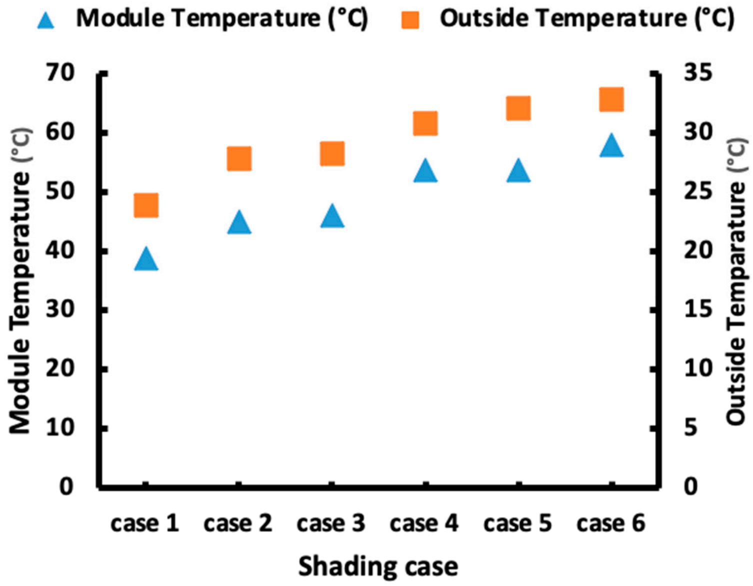


Figure 8. The effect of six different PSCs on PV array A modules' temperature.

4. Discussion

4.1. Power Output Loss

In array A, only the first PV cells of the PV modules were horizontally shaded. In Table 5, PV array A loss values for six PSCs are given. To describe the loss in PV array A due to the shading effect, the voltage loss (V_{loss}), current loss (I_{loss}), and power output loss (P_{loss}) were calculated by differentiating between the recorded values with no shading (array B) and those recorded with shading (array A) (see Tables 4 and 5).

Table 5. PV array A loss (%) values for six shading cases.

Case	Time	Shading Percentage [%]	Loss of Array A to Array B [%]		P_{mp}
			V_{mp}	I_{mp}	
Case 1	8:30	69.3	91.6	62.8	96.8
Case 2	9:00	44.3	69.3	43.3	82.6
Case 3	9:30	32.1	38.4	22.3	52.2
Case 4	10:00	21.1	9.83	4.78	14.1
Case 5	10:30	10.5	0.07	0.19	0.26
Case 6	11:00	3.2	1.74	0.00	1.70

The voltage loss (V_{loss}) is defined as Equation (3), the current loss (I_{loss}) is defined as Equation (4), and the power output loss (P_{loss}) is defined as Equation (5), as follows:

$$V_{loss} = \frac{V_{unshade} - V_{shade}}{V_{unshade}} \times 100\ (\%) \quad (3)$$

where $V_{unshade}$ is the voltage of array B with no shading and V_{shade} is the voltage of the PV array A with shading.

And:

$$I_{loss} = \frac{I_{unshade} - I_{shade}}{I_{unshade}} \times 100\ (\%) \quad (4)$$

where $I_{unshade}$ is the current of array B with no shading and I_{shade} is the current of the PV array A with shading.

And:

$$P_{loss} = \frac{P_{unshade} - P_{shade}}{P_{unshade}} \times 100\ (\%) \quad (5)$$

where $P_{unshade}$ is the power output of array B with no shading and P_{shade} is the power output of array A with shading.

Figure 9 shows PV array A voltage loss (V_{loss}), current loss (I_{loss}), and power output loss (P_{loss}) corresponding to the shading percentage. The results show that PV array A voltage loss, current loss, and power output loss were 91%, 62%, and 96% when the shading percentage was about 70% at 8:30 a.m. The voltage loss, the current loss, and the power output loss became minimal when the shading percentage was low, and about 3% at 11:00 a.m.

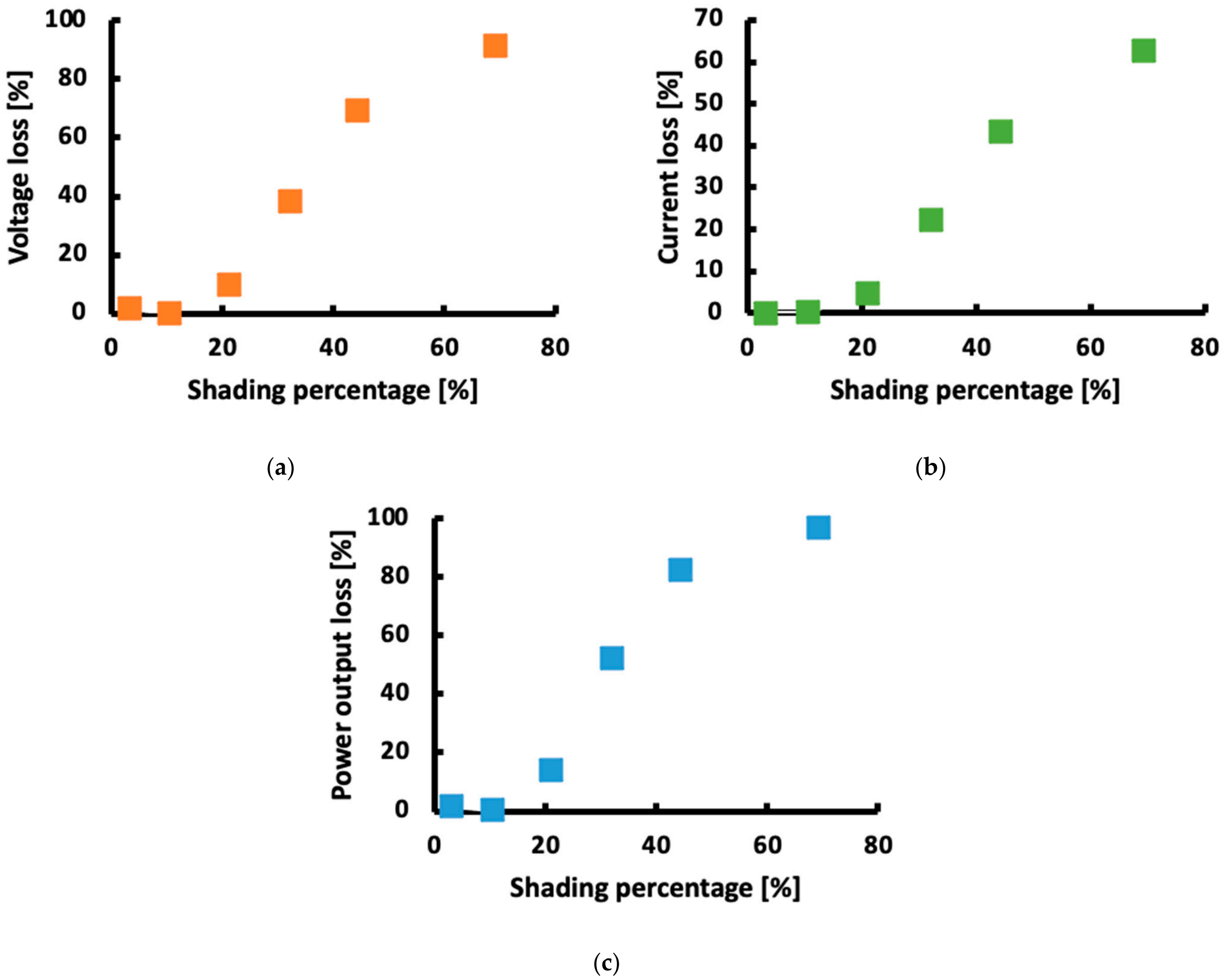


Figure 9. The relation between shading percentage on the first PV cells PV modules in array A: (**a**) voltage loss, (**b**) current loss, and (**c**) power output loss.

4.2. Fill Factor

Fill factor (FF) is the ratio of maximum power output to the product of the open-circuit voltage and short circuit current of the PV array configuration. The fill factor is given in Equation (6).

$$FF = \frac{P_{\text{mpshade}}}{V_{\text{oc}} \times I_{\text{sc}}} \tag{6}$$

where P_{mpshade}, V_{oc}, *and* I_{sc} represent the maximum power output under shading condition, the open-circuit voltage of PV array A configuration, and short-circuit current of PV array A configuration, respectively. Fill factor values for six shading cases are given in Table 6.

Table 6. Fill factor values for six shading cases.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Fill factor	0.009	0.07	0.21	0.39	0.44	0.44

For case 1, when the shading percentage is high, the fill factor value is too small. As the shading percentage decreased, the fill factor for case 6 was high when the PV array performance was higher. The fill factor for six different PSCs is shown in Figure 10.

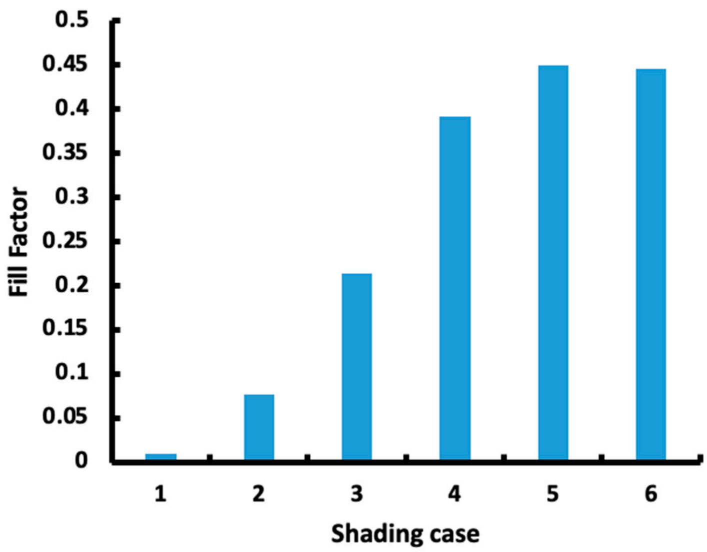


Figure 10. The fill factor for six different PSCs.

5. Conclusions and Future Work

This paper presents an experimental investigation on photovoltaic array (PV array) power output affected by partial shading conditions (PSCs). An experiment setup of PV arrays with a series configuration using 2 × 4 photovoltaic modules (PV modules) was built. The power output loss due to the shading effect on the first photovoltaic cells (PV cell) connected with bypass diodes of each photovoltaic module installed in the PV array in the horizontal direction was evaluated. Depending on the sun's direction relative to the PV array configuration, the shading percentage was measured during the test and the current and voltage of the PV array recorded. The experimental results showed that 44% shading of the first PV cells affected the PV array power output loss by more than 80%. It is seen from the results that, in the case of the series configuration of a PV array, even if only one PV module fails to generate electricity due to the event of failure or partial shading, the total amount of power generation of the whole PV array is reduced.

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