

Partially shaded characterization effect on two different single crystalline photovoltaic modules with bypass diode

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One of the main causes of losses in energy generation within photovoltaic (PV) systems is the partial shading on photovoltaic modules. A PV system can easily lose a significant portion of its total output with only minimal shading. A bypass diode in the module will form an alternating path for the current generated from the unshaded parts and prevent these cells/modules from damage in the array. Because solar cells are not designed to support a reverse voltage, they may be degraded, depending on the applied voltage. Virtually all modern PV modules include bypass diodes. The purpose of this work is the study of power decrease of a commercially available single-crystalline silicon photovoltaic module under varying shading with bypass diode. Without shading the tested module generates 75W and 120 W at maximum power under rated conditions.

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1. Introduction

Because of the increasing demand for energy and the limited supply of fossil fuels, the search for alternative sources of power is imperative. The renewable energy sources have an inexhaustible potential and at the same time they are a future energy source. Photovoltaic (PV) systems are one of the leading technologies in the field of renewable energy sources [1].

Photovoltaic modules are connected in series and parallel in order to match the requirements regarding DC voltage and current of the inverter input [2]. The total DC power in such network is, however lower than the sum of the individual rated power of each module. The main reasons are static mismatch, environmental stress and shadow problems. The first aspect is related to manufacturing tolerances and aging of the module connected in the array. The second aspect instead refers to the effect of module defects due to weather conditions [3-4]. Dynamic mismatches occurs when the modules operates far from its maximum power point. The PV modules connected in parallel or in series cannot operate in their individual maximum power point because the voltage (in case of parallel connection) or current (in case of series connection) is forced to be equal in all the modules of the string [5].

If a PV module is partially shaded, some of its cells can work in reverse bias, working as loads and not as power generators. When reverse bias exceeds the breakdown voltage of the shaded solar cell, the cell will be fully damaged; for example, cell cracking or hot spot formation appears and an open circuit exists at the serial branch where the cell is connected. If the system is not appropriately protected, hot-spot problem can arise and, in severe cases, the system can be irreversibly damaged

[1,6,7]. Nowadays, there are newer cell designs, a growing increase in average cell size and modules that are specially manufactured for their integration into buildings where partial shading can be frequent. This tendency makes the study of partial shading of modules and cell reverse characteristics a key issue. Nevertheless, there is still a lack of information related to the behaviour of commercial photovoltaic (PV) cells operating in reverse bias and their effect in case of partial shading. The objective is to prevent the shaded cell to reach the thermal breakdown, point in which it could be irreversibly damaged. The characterisation of reverse I-V curves is fundamental to extract conclusions in relation to that topic [8]. In the case of PV systems, the analysis of the different effects caused by partial shading is very useful to avoid excessive power losses, to reliably protect the system, and to determine, in case that partial shading is unavoidable, which is the best configuration to minimise the negative effects of shadings [9].

Since a long time the shading effect has been investigated by several research groups. The studies focused on the empirical description of *IV* curves [10-12], shading effect due to power loss in a module [13], the analysis and detection of shading effect in single PV module [14-16], and shading effect investigations on the PV systems [17-20].

The purpose of this work is the study of power decrease in commercially available two different single-crystalline silicon photovoltaic modules under varying shading with bypass diode. Some module parameters; efficiency, fill factor and power difference are analysed using the current voltage curves of the PV modules for different shading conditions.

2. Experimental verification

2.1. Description of the photovoltaic modules

Two commercially available single crystalline silicon PV modules are used for performance tests. 36 solar cells are connected in series to obtain 18V at open circuit voltage and 75W/120W maximum power at STC (STC: Standard Test Conditions: 1000W/m² irradiation, 25°C cell temperature under AM 1.5 conditions).

Each PV modules has 36 standard cells and built from 2 substrings. The 2 substrings are serially connected to each other to form the PV module and each substring is protected by a bypass diode (Fig. 1).

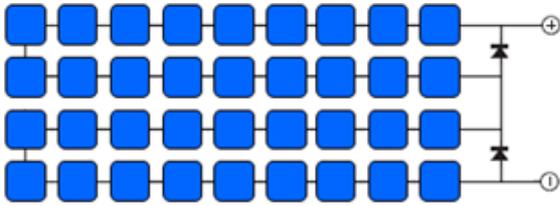


Fig 1. Cell interconnections of the PV modules.

As long as the light hitting the surface of the PV module, each uniform illuminated cell will produce approximately 0.5V and one substring voltage will be +9V where each bypass diode will have -9V at its input and will not conduct any current.

The specifications of tested PV modules under STC are given in Table 1. Although both tested modules have single crystalline silicon PV cells the sizes of the cells are different. AP75 PV module has 12X12 cm² and AP120 PV module has 15X15 cm² cells.

Table 1. PV Module Specifications under STC [21].

	AP75	AP120
Nominal Power (Wp)	75	120
Impp (A)	4.40	7.10
Vmpp (V)	17.00	16.90
Isc (A)	4.80	7.70
Voc (V)	21.00	21.00
Cell dimensions (cm ²)	12 x 12	15 x 15
Temperature coefficient for short circuit current, $\mu_{I_{sc}}$ [mA/K]	0.6	0.6
Temperature coefficient for open circuit voltage, $\mu_{V_{oc}}$ [mV/K]	-77.00	-77.00
Temperature coefficient for maximum power, $\mu_{P_{mpp}}$ [%/K]	-0.50	-0.50

2.2 Mugla Sıtkı Kocman University PV outdoor test site

A multi-channel measurement system in Mugla University Clean Energy Resources Research and Development Centre (MUTEK R&D) developed by Aescusoft. The system can scan the whole current-voltage curve of a solar cell or photovoltaic module in 20 seconds [22]. Voltage of solar cell or PV module under test is scanned at 80 points from the value around short circuit current (0V) to the open circuit voltage (V_{OC}) and current value corresponding to each voltage value is measured and saved in a file. These measurements are performed once in two minutes interval and during a day. Variations in the internal parameters of the solar cell or PV module can be observed within a day or between seasons by using the obtained current-voltage curves. 4 points measurement method is used (2 cables for load and 2 cables for sense) for the current and voltage measurements of the tested PV modules. The data recorded separately for every measurement and stored on the hard disk of a computer for analysing and evaluating the performance [23].

3. Results

A current-voltage characteristic of the module is measured for different shading configurations under 1050±20W/m² plane of array irradiation in July 27, 2012. Module operating temperature is about 55°C and the ambient temperature is about 32°C. Short circuit current, I_{sc}, open circuit voltage, V_{oc}, current and voltage at maximum power point, I_{mpp} and V_{mpp} are measured increasing the shading rate. Efficiency, η, fill factor, FF and the power difference, ΔP, of the PV module against the full illuminated power is calculated. Measured and calculated parameters are given in Table 2-5. Power difference rate is also calculated using Eqn. 1.

$$\frac{\Delta P}{P} (\%) = \frac{P_{mpp,full\ illuminated} - P_{mpp,shaded}}{P_{mpp,full\ illuminated}} \times 100 \quad (1)$$

Fig. 2 represents the shading configuration on the PV module. The half string solar cell (Shading 1), one string of solar cells (Shading 2), one and a half solar cells (Shading 3), the two string solar cells (Shading 4), two and a half string solar cells (Shading 5) and the three string solar cells on the module (Shading 6) have been shaded.

Fig. 3 and Fig. 4 show that shading has a strong influence on the current-voltage and the power-voltage characteristics of the PV module.

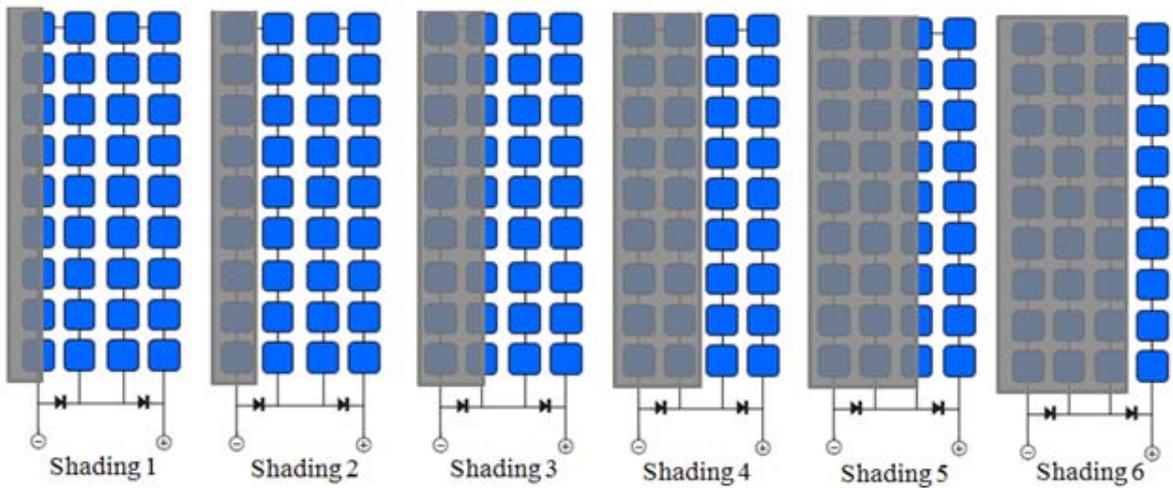


Fig. 2. Shading configuration on PV module.

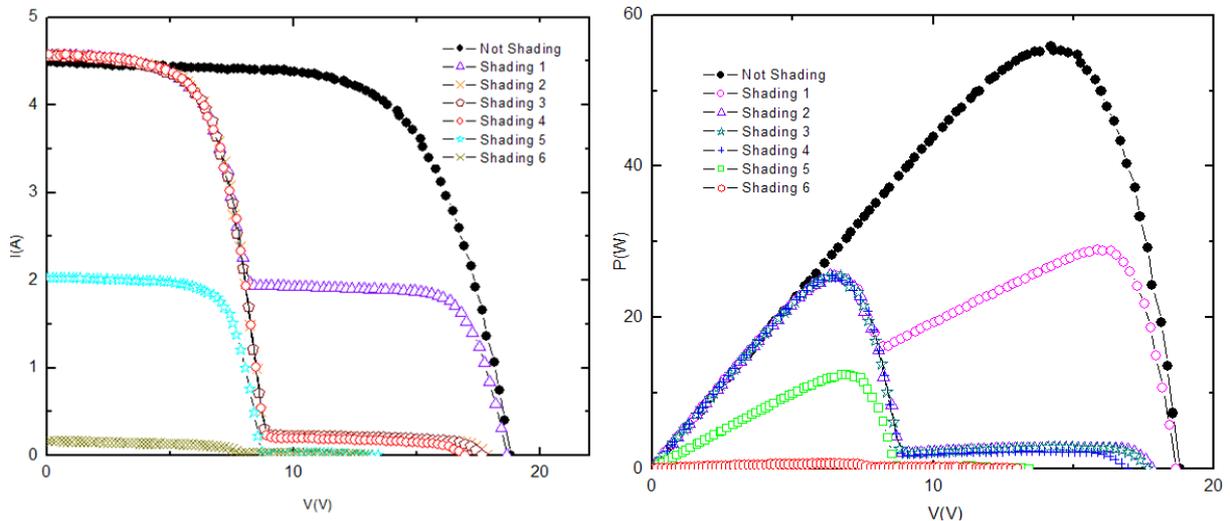


Fig. 3. Current-voltage and Power-voltage curves for different shadings of AP75 module.

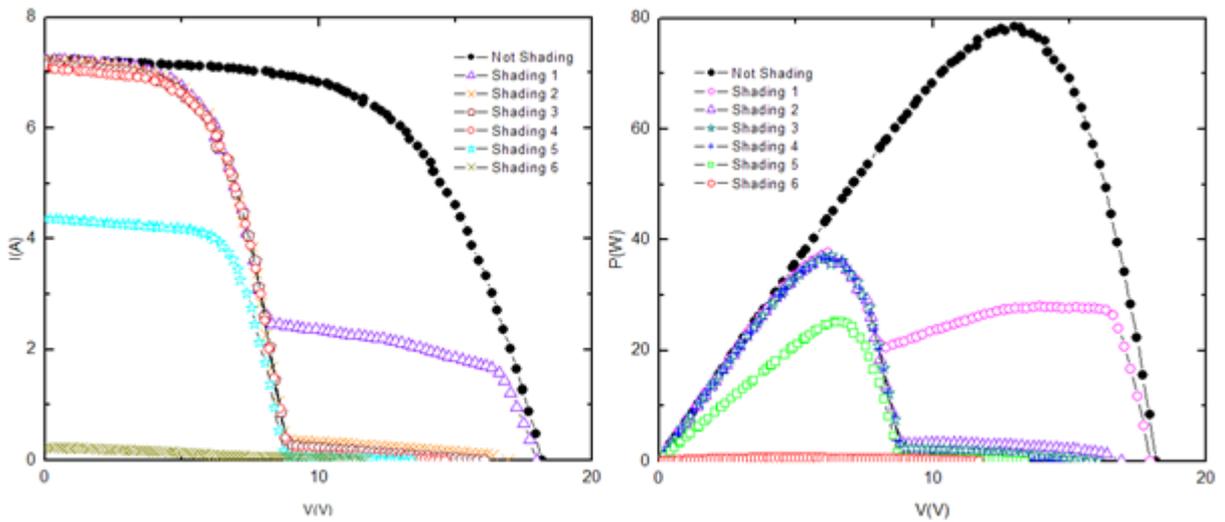


Fig. 4. Current-voltage and power-voltage curves for different shadings of AP120 module.

Under shading 1; maximum power of the AP75 PV module decreases to 28.86W from 55.80W. The power decrease ratio is 48.27% where the shading ratio on the PV module area is only 12.5%. Under shading 2; the maximum power decreases to 25.51W although one string of solar cells (25% of the module) are shaded. Under shading 3 and 4; one and a half string of solar cells (37.5%

shading of the module) and two strings of solar cells (50% shading of the module) are shaded the maximum power decreases more than 54%. When two and a half string solar cells (62.5% shading of the module) or three string solar cells (75% shading of the module) are shaded the maximum power decreases for approximately 98.78%.

Table 2. Parameters of the tested AP75 PV module under different shadings.

Shading	$V_{oc}(V)$	$I_{sc}(A)$	$I_{mpp}(A)$	$V_{mpp}(V)$	FF(%)	$\eta_{mod.}(\%)$	$\Delta P(W)$	$\Delta P/P(\%)$
Unshaded	18.80	4.48	3.93	14.20	66.25	5.58	0	0
Shading 1	18.64	4.58	1.82	15.86	33.81	2.88	26.94	48.27
Shading 2	17.79	4.57	4.03	6.33	31.37	2.55	30.29	54.28
Shading 3	17.62	4.56	3.81	6.70	31.77	2.55	30.27	54.25
Shading 4	16.94	4.57	3.99	6.38	32.88	2.54	30.34	54.38
Shading 5	13.41	2.02	1.83	6.75	45.60	1.23	43.45	77.86
Shading 6	12.98	0.16	0.11	6.18	32.73	0.06	55.12	98.78

Under shading 1; maximum power of the AP120 PV module decreases to 37.57W from 78.52W and the power decrease ratio is 52.14% where the shading ratio on the PV module area is only 12.5%. Under shading 2; the maximum power decreases to 35W although one string of solar cells (25% of the module) are shaded. This corresponds only 30% of the PV modules rated power. Under shading 3 and 4; one and a half string of solar cells

(37.5% shading of the module) and two strings of solar cells (50% shading of the module) are shaded the maximum power decreases more than 53%. When two and a half string solar cells (62.5% shading of the module) or three string solar cells (75% shading of the module) are shaded the maximum power decreases for approximately 99.21%.

Table 3. Parameters of the tested AP120 PV module under different shadings.

Shading	$V_{oc}(V)$	$I_{sc}(A)$	$I_{mpp}(A)$	$V_{mpp}(V)$	FF(%)	$\eta_{mod.}(\%)$	$\Delta P(W)$	$\Delta P/P(\%)$
Unshaded	18.15	7.23	6.04	13.00	59.83	7.85	0	0
Shading 1	17.95	7.23	6.08	6.18	28.95	3.75	40.94	52.14
Shading 2	16.91	7.21	6.24	5.93	30.35	3.70	41.51	52.87
Shading 3	16.05	7.13	5.88	6.30	32.37	3.70	41.47	52.82
Shading 4	14.63	7.08	6.16	5.95	35.38	3.66	41.86	53.32
Shading 5	13.38	4.37	3.94	6.40	43.12	2.52	53.30	67.88
Shading 6	11.67	0.22	0.12	5.13	23.97	0.06	77.90	99.21

Fig. 5 represents the shading configuration on the PV module. The half horizontal string solar cell (Shading a) a horizontal string solar cells (Shading b), one and a half horizontal string solar cells (Shading c). The two horizontal string solar cells (Shading d) have been shaded.

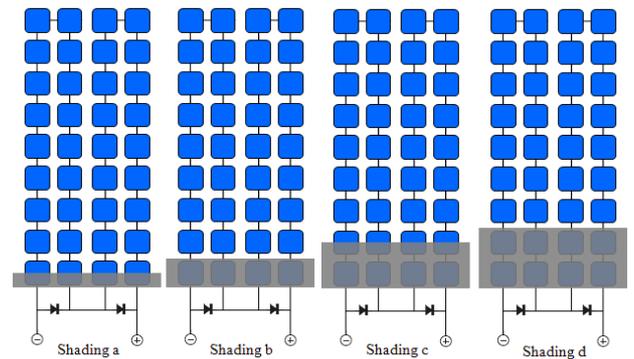


Fig. 5. Shading configuration on PV module.

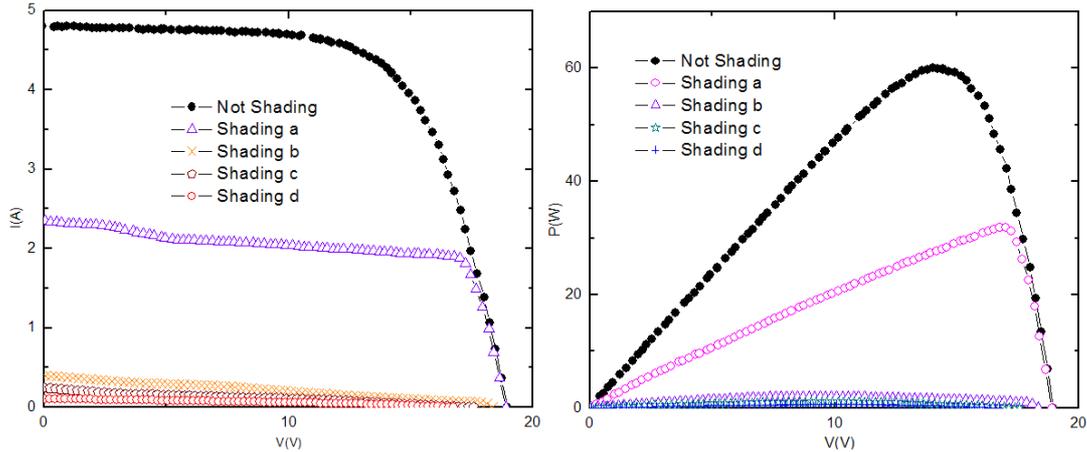


Fig. 6. Current-voltage and Power-voltage curves for different shadings of AP75 module.

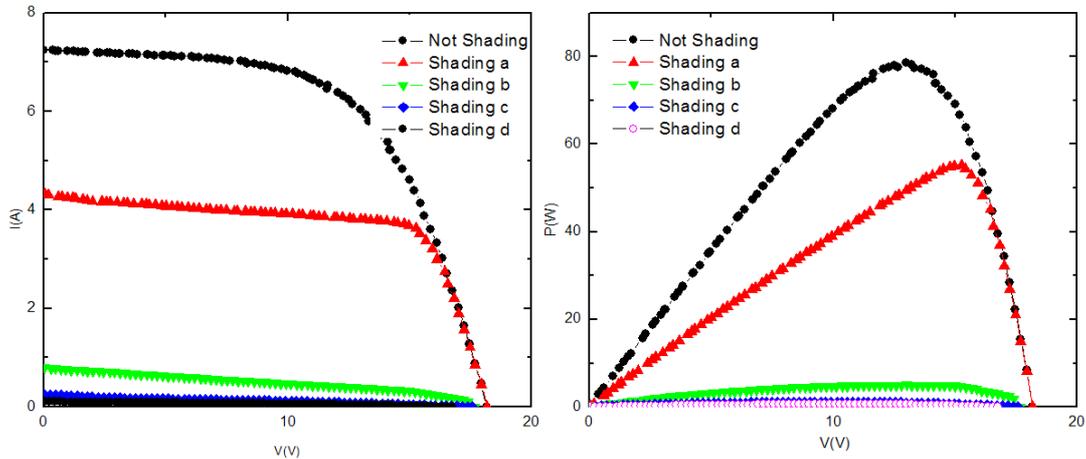


Fig. 7. Current-voltage and power-voltage curves for different shadings of AP120 module.

Table 4. Parameters of the tested AP75 PV module under different shadings.

Shading	V_{oc} (V)	I_{sc} (A)	I_{mpp} (A)	V_{mpp} (V)	FF(%)	$\eta_{mod.}$ (%)	ΔP (W)	$\Delta P/P$ (%)
Unshaded	18.95	4.80	4.27	14.04	65.90	5.59	0	0
Shading a	18.88	2.34	1.87	17.00	71.95	3.12	28.16	46.97
Shading b	18.32	0.39	0.22	8.95	27.55	0.19	57.98	96.71
Shading c	17.56	0.24	0.11	9.48	24.74	0.09	58.90	98.26
Shading d	16.75	0.10	0.05	10.27	30.65	0.04	59.43	99.14

Under shading a; maximum power of the AP75 PV module decreases to 31.79W from 59.95W and the power decrease ratio is 46.97% where the shading ratio on the PV module area is only 5.55%. Under shading b; the maximum power decreases to 1.97W although one horizontal string of solar cells (25% of the module) are

shaded. This means fewer than 10% of horizontal shading maximum power decreases approximately 97%. When one and a half horizontal string of solar cells (16.65% shading of the module) or two horizontal strings of solar cells (22.22% shading of the module) are shaded the maximum power decreases more than 98%.

Table 5. Parameters of the tested AP120 PV module under different shadings.

Shading	V_{oc} (V)	I_{sc} (A)	I_{mpp} (A)	V_{mpp} (V)	FF(%)	$\eta_{mod.}$ (%)	ΔP (W)	$\Delta P/P$ (%)
Unshaded	18.15	7.23	6.04	13.00	59.83	7.33	0	0
Shading a	18.18	4.31	3.62	15.26	70.50	5.43	23.27	29.64
Shading b	17.63	0.78	0.38	13.01	35.95	0.47	73.57	93.70
Shading c	17.56	0.24	0.11	9.48	24.74	0.09	77.47	98.67
Shading d	16.75	0.10	0.06	9.65	34.56	0.05	77.94	99.26

Under shading a; maximum power of the AP120 PV module decreases to 55.24W from 78.52W and the power decrease ratio is 29.64% where the shading ratio on the PV module area is only 5.55%. Under shading b; the maximum power decreases to 4.94W although one horizontal string of solar cells (25% of the module) are shaded. This means fewer than 10% of horizontal shading maximum power decreases approximately 94%. When one and a half horizontal string solar cells (16.65% shading of the module) or two horizontal string solar cells (22.22% shading of the module) are shaded the maximum power decreases more than 99%.

4. Conclusions

Power decrease of two commercially available single-crystalline silicon PV modules with different rating values (75W and 120W) under varying shading with bypass diode is presented. All current-voltage data are taken about 1000W/m² plane of array irradiation. Some module parameters; efficiency, fill factor and power difference are analysed using the current voltage curves of the PV module for both conditions.

The main conclusions, which may be drawn from the results of the present study, are listed below:

- Under vertical shading, although the shading ratio on the PV module area is only 25% (one vertical string of the PV module is shaded) power decrease ratio of the AP75 PV module is calculated as 54.28% where the ratio is calculated as 52.87% in AP120 PV module.
- Under horizontal shading, although the shading ratio on the PV module area is only 11% (one horizontal string of the PV module is shaded) power decrease ratio of the AP75 PV module is calculated as 96.71% where the ratio is calculated as 93.70% in AP120 PV module.

It is shown that PV module's operating power, decrease severely under partial shading and power decrease depends on the cell size. For large cells power decrease ratio is lower.

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