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Abstract: - It is a well-documented fact that partial shading of a photovoltaic array reduces it output power capability. However, the relative amount of such degradation in energy production cannot be determined in a straight forward manner, as it is often not proportional to the shaded area. This paper clarifies the mechanism of partial PV shading on a number of PV cells connected in series and/or parallel with and without bypass diodes. The analysis is presented in simple terms and can be useful to someone who wishes to determine the impact of some shading geometry on a PV system. The analysis is illustrated by measurements on a commercial 70 W panel, and a 14.4 kW PV array.

Key-Words: - photovoltaic systems, effect of shading, modeling and simulation, module layout, power production.

1 Introduction

The photovoltaic (PV) industry is experiencing rapid growth due to improving technology, lower cost, government subsidies, standardized interconnection to the electric utility grid, and public enthusiasm for an environmentally benign energy source [1]-[2]. More precisely, PV usage worldwide has grown between 15% and 40% for each of the past 10 years, while the inflation adjusted cost of PV energy has declined by roughly by a factor of 2 over the same time period [3].

PV system sizes vary from the MW range, in utility applications, down to the kW range in residential applications. In the latter systems, the PV array is typically installed on the roof of a house, and partial shading of the cells from neighboring structures or trees is often inevitable. Then impact of partial shading on PV system performance has been studied at great length in the past [4]-[11]. Some past studies assume that the decrease in power production is proportional to the shaded area and reduction in solar irradiance, thus introducing the concept of shading factor. While this concept is true for a single cell, the decrease in power at the module or array level is often far from linearity with the shaded portion. Other past studies tend to be rather complicated and difficult to follow by someone with limited knowledge on electronic/solid-state physics.

The objective of this study is to clarify the impact of shading on a solar panel performance in relatively simple terms that can be followed by a power engineer or PV system designer without difficulty. First, the circuit model of a PV cell and its I-V curve are reviewed. This is followed by the impact of partial shading on the I-V and P-V curves of a circuit containing two cells with and without bypass diodes. The concept is extended to the circuits with series and parallel submodules. Finally, the impact of shading is illustrated by measurements on a commercial PV panel and a large PV array.

2 V-I Characteristics of a PV Cell

The most commonly used circuit model to describe the electrical behavior of a PV cell is the single diode model as shown in Fig.1 below [9], [12], [13]. The current generated by the cell is expressed by

$$i = I_{ph} - I_o\left(e^{\frac{v+iR_S}{n_S V_t}} - 1\right) - \frac{v+iR_s}{R_{sh}} \quad (1)$$

where the junction thermal voltage V_t is defined by

$$V_t = \frac{AkT}{q}. \quad (2)$$

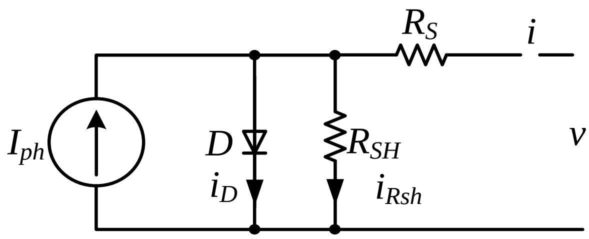


Fig. 1: Equivalent circuit of PV cell using single diode model.

The circuit parameters defined in Equations (1) and (2) are defined as follows:

I_{ph} - photo-generated current,
I_o - dark saturation current,
R_s - panel series resistance,
R_{sh} - panel parallel (or shunt) resistance,
A - diode quality (or ideality) factor,
k - Boltzmann's constant,
q - electron charge,
n^s - number of cells connected in series,
T - cell temperature (in degree Kelvin).

It is a common practice to neglect the term '-1' in Equation (1) since the dark saturation current is very small compared to the exponential term in silicon devices. Fig. 2 below shows typical I-V curves of a crystalline silicon (c-Si) PV cell at different irradiance intensity G at standard temperature condition of 25°C.

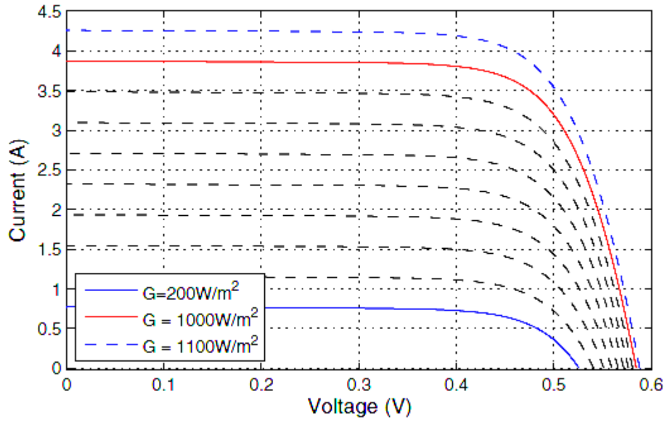


Fig. 2. Forward I-V characteristic of c-Si PV cell at different irradiance intensities.

3 Shading of Series-Connected Cells

Today, commercial c-Si PV panels usually have all their cells connected in series. In order to protect the cells from destructive reverse voltages in case of shadowing or other abnormalities, a number of bypass diodes are utilized. For example, one bypass diode connected in parallel with each set of 18 cells is common practice [11]. In this Section, the operation of the bypass diode is illustrated by a simple example where two series-connected cells, with different irradiation intensities on their surfaces, serve a resistive load as illustrated in Fig. 3 below. It is assumed that the shaded cell irradiation is 25% of the non-shaded cell as indicated by the individual I-V curves in Fig. 4(a).

Two cases are considered: In the first case, the shaded cell has an ideal bypass diode (with negligible forward bias voltage and series resistance) connected in parallel. If one varies the load resistance R_{load} from infinity to zero, the I-V curve of such configuration is shown in red Fig. 4(a). Note that the voltage of the shaded cell falls to zero when the load current exceeds the cell's short-circuit current. Hence, for higher load, the shaded cell is short-circuited and does not contribute any power.

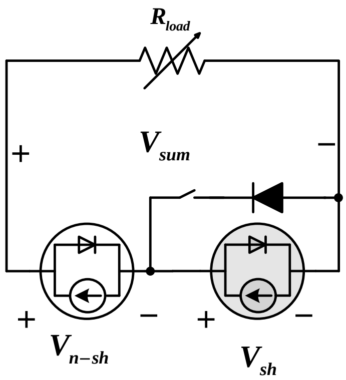


Fig. 3. Two PV cells with different irradiance intensities connected in series (with and w/o bypass diode in parallel with shaded cell).

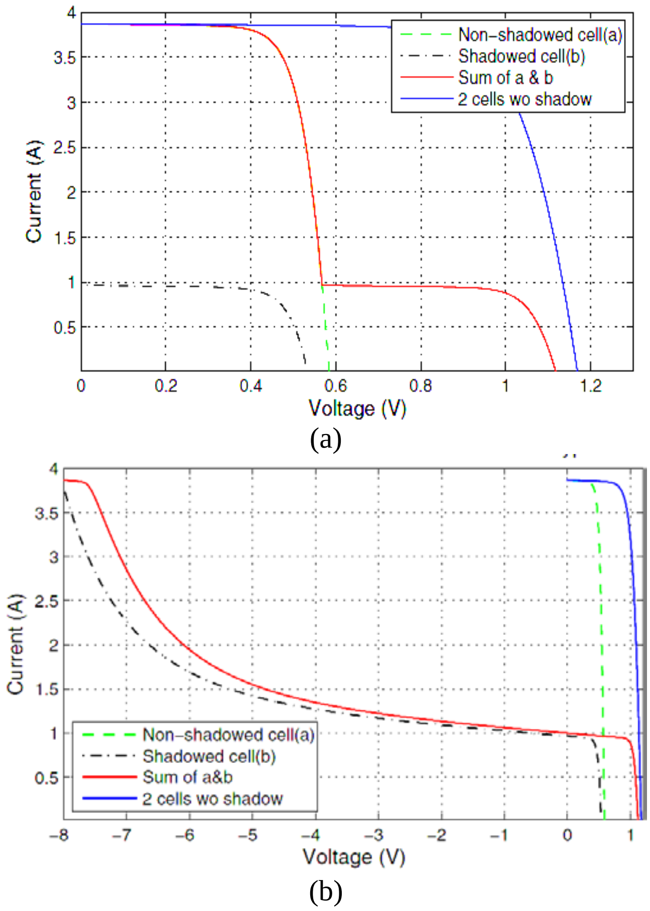


Fig. 4. I-V characteristic of two PV cells connected in series with different solar irradiance intensities: (a) with and (b) w/o bypass diode in parallel with shaded cell.

The second case considered is when the bypass diode is removed. The resultant I-V characteristics of this configuration are shown in Fig. 4(b). When the load is lower than the shaded cell short-circuit current, the circuit behaves just like the previous case (under the presence of the bypass diode). But as the load is

increased beyond this value, the shaded cell becomes reverse biased and starts to behave like a high resistor. In other words, the shaded cell starts to consume some of the power produced by the non-shaded cell thus resulting in undesirable losses. The reverse-biased region of the I-V curve is obtained by modifying the cell model in Eqn. (1) according to Refs. [9] and [11].
Figure 5 shows the corresponding power-voltage curves for the above two cases, in addition to the case without shading in both cells. Note that without the bypass diode, maximum power is reduced by nearly 50%. On the other hand, the presence of the bypass diode results is a power curve with multiple peaks.

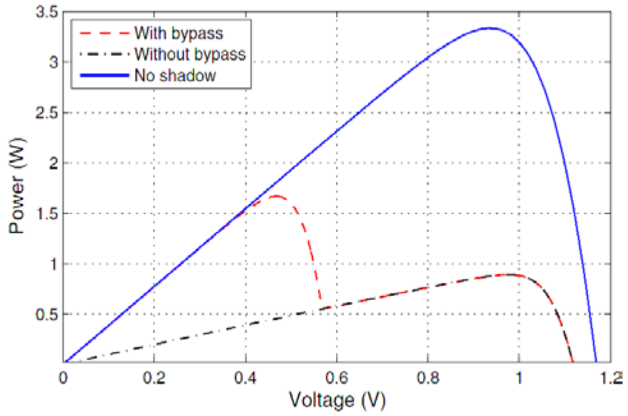


Fig. 5. P-V characteristics of two PV cells connected in series with different solar irradiance intensities (with and w/o bypass diode).

4 Partial Shading of PV Modules

As mentioned in Section 3 above, it is a common practice to use one bypass diode per 18 series-connected cells, which form the so-called submodule [6]. Furthermore, a PV module is likely to contain a number of submodules in series [13], and higher output voltage is obtained by connecting several modules in series to form a PV array. For higher power, a number of PV arrays are connected in parallel. The following material analyzes the impact of shading on part of a module which consists of series as well as parallel submodules that are protected by bypass diodes.

4.1 Partial shading of two series-connected submodules

Consider a module that consists of two series connected submodules (each containing 36 cells) with partial shading as shown in Fig. 6. For illustration, it is assumed that the clear and shadowed areas have a solar irradiance of G_{STD} = 1000 W/m^2 and G_{SH} = 250 W/m^2, respectively. Further, the bypass diodes are assumed to have a forward voltage of V_d = 0.6 V and an on-resistance of R_d = 10 mΩ. Shadowing only two cells can cause a considerable reduction in output power, and the amount of loss greatly depends on which two cells are shadowed. Two cases are considered: Case A where the two shaded cells belong to the same string, and Case B where these cells belong to different strings.

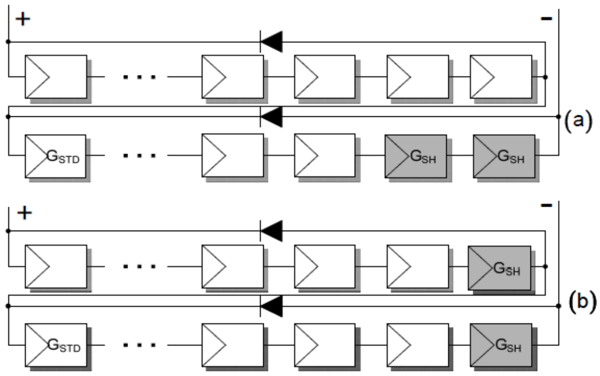
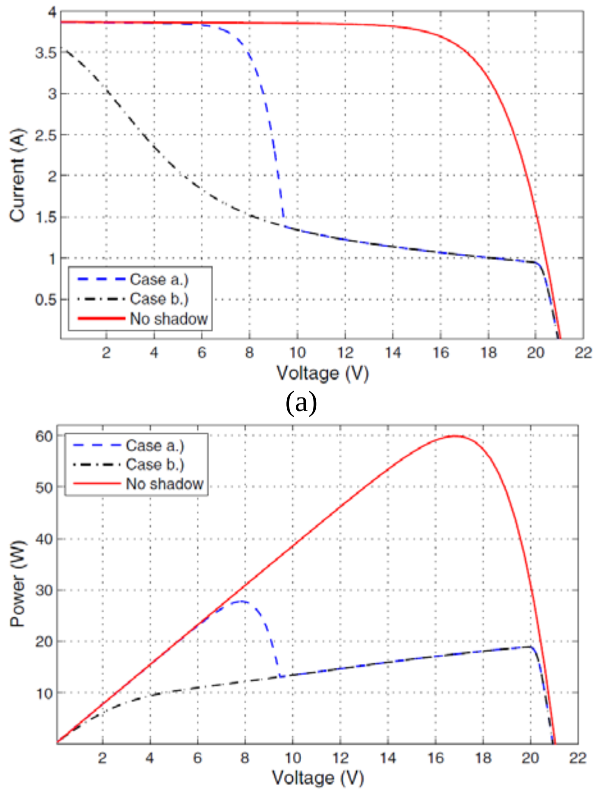


Fig. 6. Series connection of two submodules: (a) two cells shaded in one submodule, (b) one cell shaded in each submodule.

4.1.1 Case A

In Fig. 6(a), the shadowed cell will limit the output current of the submodule as explained in Section 3 above. This has a similar effect as if the whole bottom submodule is shadowed. However, as there is a bypass diode in parallel, the non-shadowed submodule can still produce full power. These remarks are demonstrated by the blue dotted I-V and P-V curves in Fig. 7.



(b)

Fig. 7. Characteristics of the two partially shaded series-connected submodules: (a) I-V characteristic, (b) P-V characteristic.

4.1.2. Case B

In Fig. 6(b) both submodules have one shadowed PV cell; hence, their output power will be both limited by the same amount. The bypass diodes will have no effect in this case, and the total power output is almost as low as if the entire string is shadowed. The resulting I-V and P-V curves for this case are shown by the dotted dark curves in Fig. 7(a) and 7(b), respectively.

In summary, although only 2 out of 36 cells are shadowed (that is less than 6% of the total area), the maximum power reduction in Cases A and B are 50% and 70%, respectively. This clearly illustrates that it is erroneous to assume that maximum power production is proportional to the non-shaded area of a PV module.

4.2 Partial shading of two parallel-connected submodules

This configuration considers the same two submodules described in Section 4.2 above with two shaded cells, but connected in parallel, instead of series, as illustrated in Fig. 8 below. Once again, the same two cases are considered. Fig. 9 shows the corresponding I-V and P-V curves the 72-cell module for both cases.

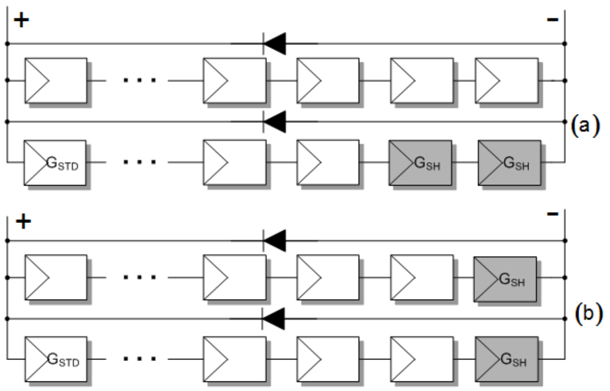


Fig. 8. Parallel connection of two submodules: (a) two cells shaded in one submodule, (b) one cell shaded in each submodule.

Note that the maximum power curve of Case B is the same as that of Case B of the previous section (i.e., max. power reduced by 70%). On the other hand, maximum power in Case A is reduced by only 35% (compared to 50% in Case A of the previous section). This is due to the fact that the cell output current shows a stronger dependency (linear) on irradiation than the voltage (logarithmic).

Alternatively, when two submodules with irradiation intensities are connected together, the relative difference of their maximum power point (MPP) currents is much larger than the relative difference of their MPP voltages. Therefore, in case of the series connection, if one submodule is working at its MPP, the other submodule having the same current works far from its MPP. The opposite is true in the parallel connection (i.e., if one submodule is working at its MPP, the other one sharing the same voltage will work also in the vicinity of its MPP, thus resulting in a higher MPP power).

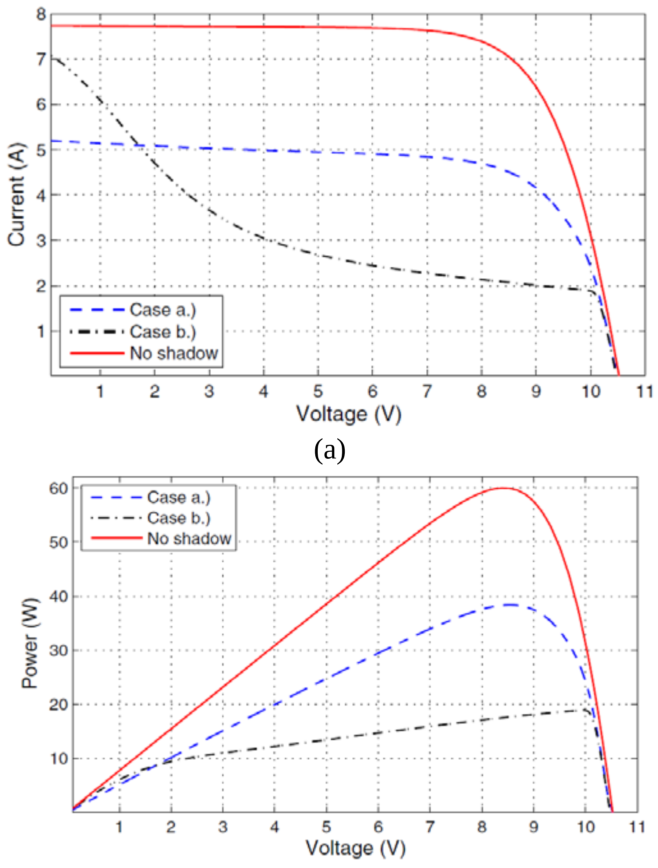


Fig. 9. Characteristics of the two partially shaded parallel-connected submodules: (a) I-V Characteristic, (b) P-V characteristic.

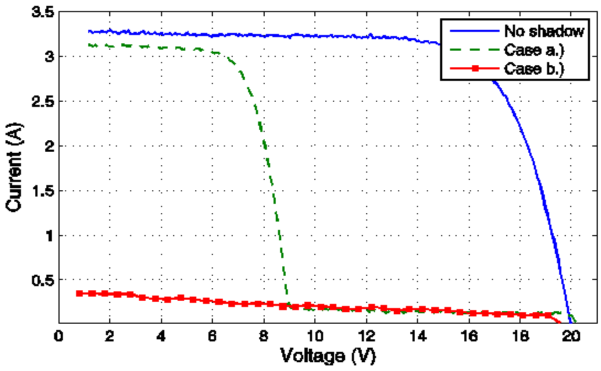
5 Experimental Test

In order to verify some of the simulated curves of the previous section, an experiment was conducted on a Kyocera KC70 multi-crystalline silicone PV panel using a Daystar-100 I-V curve tracer. The electrical specs of the 70 W panel are as follows (at standard temperature conditions):

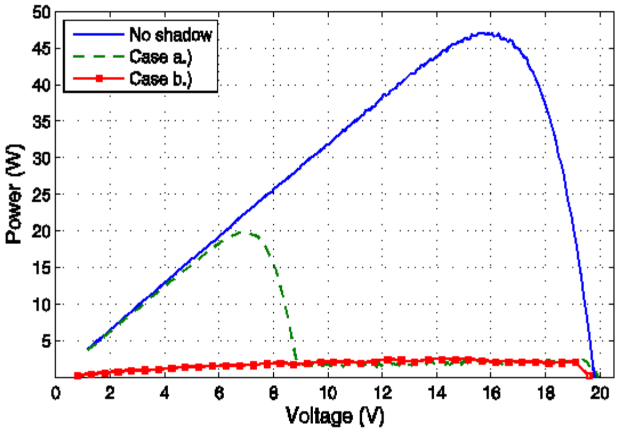
- short-circuit current: I_{sc} = 4.35 A
- open-circuit voltage: V_{oc} = 21.5 A
- voltage at MPP**:** V_{mpp} = 16.9 V
- current at MPP: I_{mpp} = 14.14 A
- power at MPP: P_{max} = 70 W
- temp. coefficient of I_{sc}: $k_t = 3.55\ 10^{-3}$ /°C
- temp. coefficient of V_{sc}: $k_v = -8.2\ 10^{-2}$ /°C.

The Kyocera KC70 photovoltaic panel has the electrical configuration of the cells and bypass diodes identical to the case depicted in Fig. 6. To create a partial shadowing condition, 2 cells belonging to the same submodule were covered with a sheet of cardboard, which makes the shadowing close to 100%, i.e., near zero solar irradiation on the covered area. The measurement results shown in

Fig. 10 below show a good agreement with the predicted curves associated with Section 4.1.1.



(a)



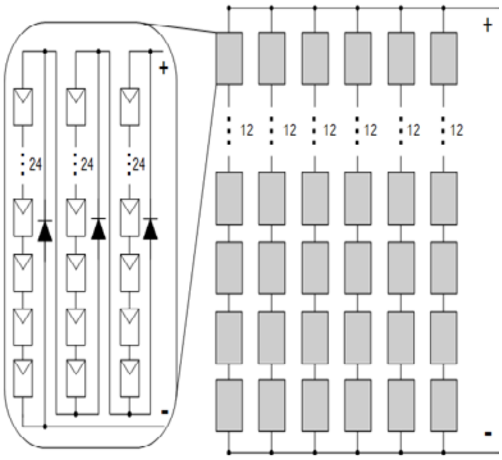
(b)

Fig. 10. Experimental data of Kyocera KC70 PV panel with two shaded cells: (a) V-I characteristic, (b) P-V characteristic.

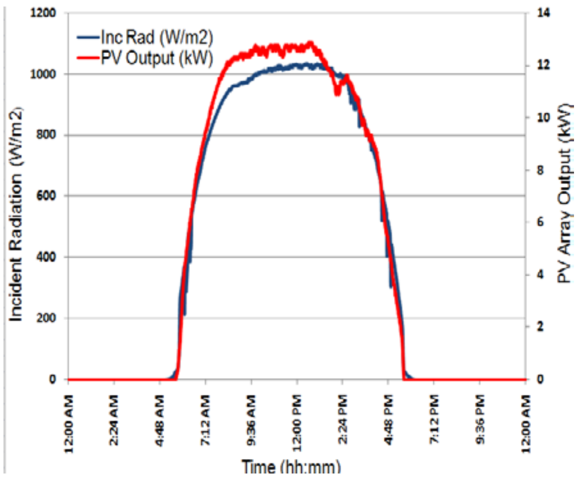
The next field data involves the impact of partial shading on the performance of a grid-connected, 14.4 kW, 1-axis tracking, PV system that is located in Las Vegas, Nevada. The system consists of 4 identical tracking sub-arrays, as shown in Fig. 11(a), each of which contains two parallel strings of 12 series-connected panels. Herein, each panel is rated at 150 W (each) and consists of 3 series-connected submodules with bypass diodes. Each submodule contains 24 cells connected in series as illustrated in Fig. 11(b). In summary, the array contains 8 parallel strings, each containing 36 submodules and 864 cells.

Fig. 11(c) shows a typical power production curve (in kW) of the array along with the incident solar radiation (in W/m^2) on a clear day. One can immediately note the dip in power production between the hours of 1:00 pm and 3:00 pm on this particular day of 9/11/08. A closer analysis showed that a power pole (only its shadow can be seen in the photo) shaded part of the front sub-array during those hours of that day. Further work will be conducted to estimate the yearly energy reduction due to shading of this structure. The variation of the shadow on the photovoltaic collector will be determined by using techniques such as the one proposed in Ref. [16].


(a)



(b)



(c)

Fig. 11 14.4 kW grid-connected PV system: (a) actual array, (b) connection diagram, (c) power production on 9/11/08.

6 Conclusion

This paper presented the impact of shading on the I-V and P-C curves of a solar panel, and clarified the basic mechanism that estimates the reduction in output power. Such degradation in maximum power production clearly depends on the shaded area as well as the layout of the submodules and the bypass diodes. The analysis was illustrated by experimental data. It is hoped that this article will be of use to PV system designers when attempting to minimize the impact of shading on system performance.

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