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Technical Note

# Computer simulation of shading effects in photovoltaic arrays

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**Abstract**

A simulation of shading effects in arrays with different string configurations has been done. Simulation has been performed using as the basic unit the solar cell, modelled in direct bias by the conventional one exponential model, and in reverse bias by an equation previously validated in different types of photovoltaic cells reverse characteristics. The influence of the amount of shading, the type of reverse characteristic of the cell, the string length and the number of shaded cells has been analysed, and some recommendations are extracted.


*Keywords:* Shading; Simulation; PV array

## 1. Introduction

Computer simulation is a valuable tool since it makes possible to predict a great variability of situations and occurrences in the performance of a system. In the case of photovoltaic 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.

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There are several commercial programmes that include the possibility of evaluating the behaviour of a system in presence of shading. One can mention, for example, the widely known PVSYST [1]. Woyte et al. [2] carried out an analysis based in a market survey of an international journal [3]. Following this publication, only one of the simulation programmes mentioned in the survey lead the analysis to the level of the solar cell [4], even though it has been proved the influence of the type of reverse characteristic in case of partial shading [5–7]. The so-called program PVSIM [8], although not included in such revision, is one of the few allowing this possibility. It uses Bishop's equation [9] to model the reverse characteristic of the cells. Other publications in relation to shading effects use also the mentioned model [10,11], though the great differences in the reverse characteristics of same type cells are not usually considered.

The purpose of this paper is to illustrate, by analysing different shading situations, the effects that partial shading can cause in a PV array. It is a complementary work of a previous analysis in which such effects have been proved experimentally [7,12]. The equation used in the simulation has been previously validated in a set of different reverse characteristics of several PV cells [13], and is a close packed formula of a more comprehensive one obtained from the analysis of breakdown phenomena in PV solar cells [14].

The advantage of computer simulation is that different cases can be easily evaluated, although in case of partial shading it is also important to determine the heat distribution along cell surface.

## 2. Formulation of the simulation

Solar cell is assumed as the basic unit of the simulation. Solar cell has been modelled in direct bias according to the well known one exponential model:

$$I = I_L - I_0\left[\exp\left(\frac{V + IR_s}{mV_T}\right) - 1\right] - (V + IR_s)G_p, \tag{1}$$

where model parameters have their usual meanings.

In reverse bias, an equation validated for a great variability of reverse characteristics [13] has been used:

$$I = \frac{I_{sc} - G_p V + cV^2}{1 - \exp\{B_e(1 - \sqrt{(\phi_T - V_b) - (\phi_T - V)})\}}, \tag{2}$$

where $B_e$ is a non-dimensional cuasi-constant parameter with value [14]~3, $V_b$ is breakdown voltage, $\Phi_T$ is the built-in junction voltage (not to be used as an adjustable parameter. For silicon cells of unknown junction structure a typical value, for example $\Phi_T = 0.85\,\mathrm{V}$, should instead be considered), and $G_p$ is shunt conductance (the same $G_p$ than in Eq. (1)).

In all cases it has been considered that by-pass diodes are used, as they are usually employed in real applications. By-pass diode has been simulated as a straight line with infinite slope and intercept at $-0.8\,\mathrm{V}$.

Several cases have been analysed:

- Influence of the amount of shading. It has been simulated considering that photocurrent and short circuit current decrease in the same way that amount of shading does. The rest of the parameters do not change.

- Influence of the type of reverse characteristic of the shaded cell. It has been simulated by changing model parameters in the reverse bias equation. In Eq. (2), model parameters with more influence in case of partial shading in a string are $G_p$ and $c$. Shunt conductance, $G_p$, gives the slope of the characteristic for low voltages, and $c$ modifies slightly its curvature. Taking into account that by-pass diodes are used, and that $c$ influence is small compared to $G_p$, only $G_p$ variations have been considered, as an indicative of the different reverse characteristics that may exist in real cases.
- Influence of string length.
- Influence of the number of shaded cells.

## 3. Results

### 3.1. Influence of the amount of shading

A string with 18 cells has been considered, supposing that one of the cells is 25%, 50%, 75% or 100% shaded. A system formed by 3 and 6 strings serially connected has been simulated. Results are presented in Figs. 1(a,b). Short circuit reduction of shaded cell is evidenced in the reduction of current at which shading effects begin to be appreciated (point A in Fig. 1), and in the reduction of the current at which by-pass diode is activated (point B in Fig. 1).

Herrmann et al. [15,16] have proposed the definition of a critical shading rate in which positive voltages of the unshaded cells in the string compensate the negative voltage of the shaded one. This is the shading rate in which power dissipation is maximum. If we consider a system working in the maximum power point, and supposing that by-pass diode is acting, system working point will be given by

$$I_m = (I_B - I_A) + \left(1 - \frac{\Gamma}{100}\right) I_{sc} + I_D, \tag{3}$$

where $I_A$ is the point in the characteristic from which shading effects begin to be appreciated, $I_B$ is the system current from which by-pass diode starts working (see Fig. 1a),

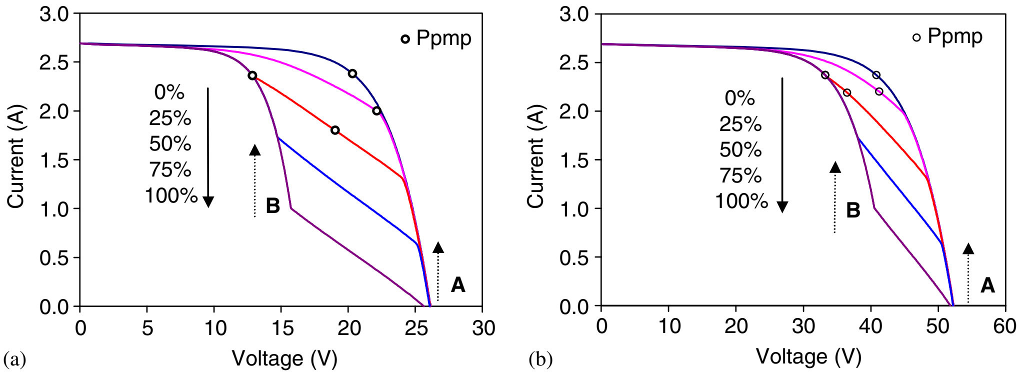


Fig. 1. Influence of shading one cell different percentages in a 18 cell strings in a system with (a) three strings (3 × (18s)) and (b) six strings (6 × (18s)).

$\Gamma$ is the shading rate, $I_{sc}$ is the short circuit current of the right cell and $I_D$ is the current through by-pass diode. If current through by-pass diode is zero, power dissipation will be maximum, and critical shading rate $\Gamma_{crit}$ can be calculated as

$$\left(1 - \frac{\Gamma_{crit}}{100}\right) = \frac{I_m - (I_B - I_A)}{I_{sc}},$$
$$\Gamma_{crit} = \left(1 - \frac{I_m - (I_B - I_A)}{I_{sc}}\right) 100. \tag{4}$$

There is also another effect due to the shading, that is a displacement of maximum power point to voltage values lower than the ones that could be foreseen for these configurations. This effect must be taken into account in case of systems connected to inverters tracking the maximum power point (mpp), as it could cause bad operation [17] and increase the losses.

### 3.2. Influence of the reverse characteristic of the shaded cell

The influence of the reverse characteristic of the shaded cell is appreciated in the zone between the point at which the $I_{sc}$ of the shaded cell is surpassed and the point at which by-pass diode is activated. Cells with high shunt conductance produce less effect in the deformation of the $I$–$V$ characteristic. An example is shown in Fig. 2, where $G_p$ parameter has been changed from 0.04 to 0.2 A/V for a completely shaded cell in a 18 cell serially connected string.

### 3.3. Influence of string length

This effect has been analysed by shading completely one cell in a system formed by 108 PV cells in which the number of cells protected by the by-pass diode has been changed according to:

- 1 diode across 18 cells and 6 strings: $6 \times (18s)$,
- 1 diode across 27 cells and 4 strings: $4 \times (27s)$,

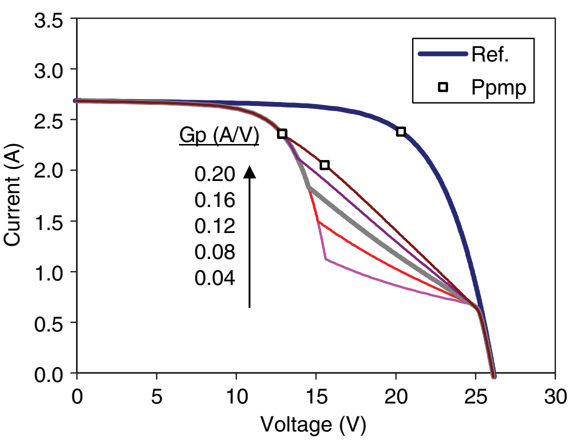


Fig. 2. Influence of reverse characteristic of the shaded cell. Type of shading: 1 cell 75% shaded. Configuration: $3 \times (18s)$.

- 1 diode across 36 cells and 3 strings: 3 × (36s),
- 1 diode across 54 cells and 2 strings: 2 × (54s).

Results can be observed in Fig. 3. The increase in the number of cells protected by the by-pass diode produces a higher deformation in the *I–V* characteristic, what, in its turn, causes a higher reduction in maximum power. Besides, more power is dissipated in the shaded cell and less current flows through the by-pass diode. Maximum power values, together with their corresponding currents and voltages are shown in Table 1, where differences in the power reduction due to the configuration can be appreciated.

### 3.4. *Influence of the number of shaded cells*

In this case it is important to distinguish between several cells shaded in the same string or in different strings. The following notation is used to evaluate this case:

- *String A*: 18 cells serially connected (18s) all of them working properly.
- *String B1*: 18s, 17 cells working properly and one cell 75% shaded.
- *String B2*: 18s, 16 cells working properly and two cells 75% shaded.
- *String B3*: 18s, 15 cells working properly and three cells 75% shaded.
- *String Bn*: 18s, (18-*n*) cells working properly and *n* cells 75% shaded.

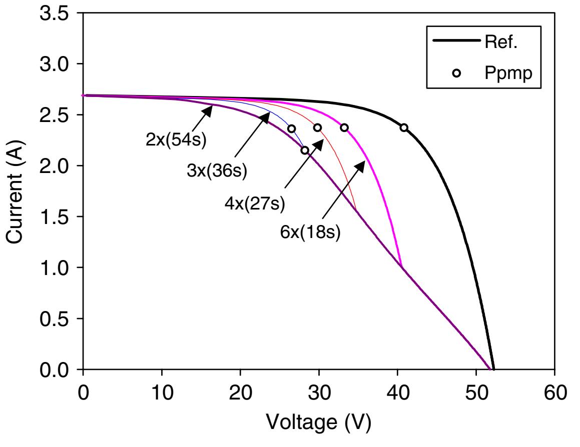


Fig. 3. Effect of string length when shading completely one cell in different string configurations.

Table 1
Maximum power point values, with their corresponding currents and voltages, for the characteristics of Fig. 3

| Configuration | $P_{pmp}$ (W) | $V_{pmp}$ (V) | $I_{pmp}$ (A) |
|---|---|---|---|
| 108s | 96.8 | 40.9 | 2.37 |
| 6 × (18s) | 78.8 | 33.2 | 2.37 |
| 4 × (27s) | 70.7 | 29.8 | 2.37 |
| 3 × (36s) | 62.6 | 26.5 | 2.36 |
| 2 × (54s) | 60.7 | 28.2 | 2.15 |

Fig. 4 presents the effect of increasing the number of shaded cells in a string with 18 cells serially connected. This effect is reflected when several strings are associated, as it can be appreciated in Fig. 5. Fig. 5(a) shows a system formed by three strings of 18 cells serially connected 3 × (18s), in which one, two or three cells in one string have been shaded 75%. Notation used in the figure is the one described above. The deformation of the *I–V* characteristic increases with the number of shaded cells, what is a consequence of the decrease in the string short circuit current when the number of shaded cells is increased (see Fig. 4). In case of a system working in the maximum power point, the increase in the number of shaded cells in a string has no effect, as maximum power point is the same for the three characteristics showed in Fig. 5.

Results are completely different when cells are shaded in different strings, since in this case the increase in the number of shaded cells causes a great reduction in mpp. An example is shown in Fig. 5(b). Maximum power point values for this figure are presented in Table 2, showing a reduction in power of 61% for the case in which the same shading is

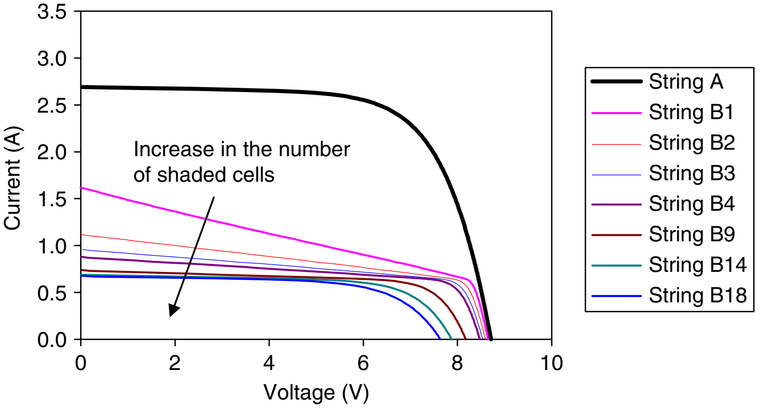


Fig. 4. Effect of increasing the number of shaded cells in a 18s string.

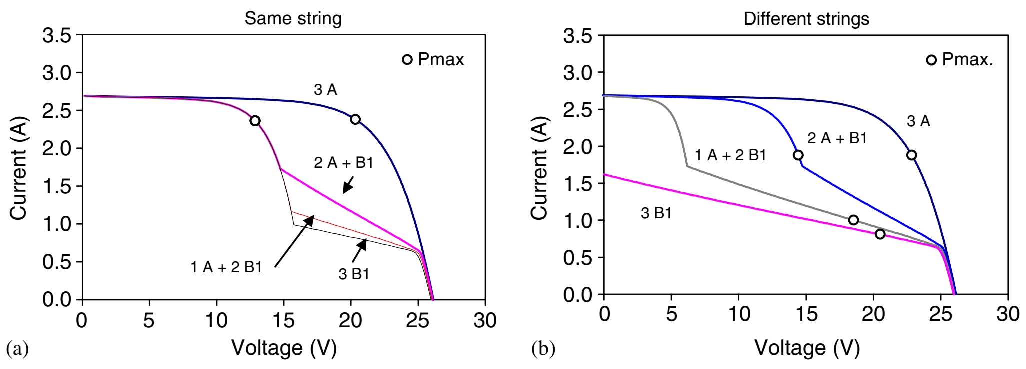


Fig. 5. Effect of increase the number of shaded cells in a 3 × (18s) system when (a) shaded cells are in the same string and (b) shaded cells are in different strings. Notation: string A: 18 cells serially connected, string B1: 18 cells serially connected with one cell 75% shaded, 3A: three strings A type serially connected, 2A + B1: 2 strings A type and one B1 type serially connected, and so on.

Table 2
Maximum power point values, with their corresponding currents and voltages, for the characteristics of Fig. 5(b)

| Configuration | $P_{pmp}$ (W) | $V_{pmp}$ (V) | $I_{pmp}$ (A) |
|---|---|---|---|
| 3A | 43.0 | 22.8 | 1.88 |
| 2A + B1 | 27.1 | 14.4 | 1.88 |
| 1A + 2B1 | 18.5 | 18.5 | 1.00 |
| 3B1 | 16.6 | 20.5 | 0.81 |

present in all the strings of the array. This is a case that should be avoided, as it produces maximum power reduction.

## 4. Conclusions

Main conclusion of this work are addressed to emphasise the importance of reverse bias characterisation of PV cells, and to analyse string distributions when part of a system is going to be shaded during its lifetime. Following conclusions are obtained from cases analysed with the simulation:

(1) The increase of shading rate over one cell produces higher deformations in the *I–V* characteristic, at the same time that displaces mpp voltage to lower values.
(2) Cells with higher shunt conductances (lower shunt resistance) cause smaller deformation in the resulting *I–V* characteristic.
(3) The increase in the number of cells per string causes higher deformation in the *I–V* characteristic, displaces the working point to lower voltages and increases power losses.
(4) The increase in the number of shaded cells in the same string do not affect mpp, nevertheless when cells are placed in different strings power losses are considerably increased.

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