

## Shading Effects on Output Power of Grid Connected Photovoltaic Generator Systems

R. E. Hanitsch, Detlef Schulz and Udo Siegfried

Technical University Berlin · Institute of Electrical Power- and Automation Technology  
Sec. EM 4 · Einsteinufer 11 · D-10587 Berlin · Germany

**Abstract** – *the quality of power supply from photovoltaic generators is very sensitive to shading effects of single or multiple cells. The energy yield of a partly shaded photovoltaic system is much lower than we could assume from the mean solar irradiance. Therefore we have to optimise the module structure and to select the right type of maximum power point tracking system in combination with the solar inverter.*

**Résumé** – *la qualité d'une puissance électrique produite par un générateur photovoltaïque reste très sensible à l'effet d'ombre produit par une ou plusieurs cellules. Ainsi, dans un système photovoltaïque, le rendement énergétique produit par ce phénomène d'ombre est beaucoup plus faible par rapport à l'irradiance solaire moyenne. C'est pourquoi, nous devons optimiser la structure du module et choisir le système de poursuite et de mesure de la puissance maximale en combinaison avec le convertisseur solaire.*

**Keywords:** Power supply – Photovoltaic generators – Shading effects – Solar irradiance.

### 1. INTRODUCTION

From case studies it is known that PV systems with the same nominal power generate quite different energy yields due to different shading patterns. The typical problems are:

- reduction of power output: As the insolation is reduced by shading we get a reduced photo current. Because of the series connection of all the cells the current for all the cells is reduced.
- thermal stress on the module: Depending on the level of shading, the PV generator circuit and the load the voltage of shaded cells might reverse.

In this case they operate in the blocking state as a resistive load. The losses in the individual cell can increase the cell temperature dramatically and overheating might occur. Inhomogenities of the cell might result in hot spots, local defects due to high temperatures.

In order to overcome some of the problems related to shading, by-pass-diodes are connected parallel to a number of solar cells. Under normal operating conditions the diodes are blocked compared to the voltage generated by the cells. When shading occurs the reversal of the voltage can be observed in that specific section and now the by-pass diode in parallel will conduct the current. The results are:

- The current of the unshaded section flows through the by-pass diode and the power/voltage characteristic shows a second local maximum
- The shaded cell is only loaded with that fraction of power produced by the remaining unshaded cells of that section
- When the number of cells which are bridged by the by-pass diode is not too high, the level of the break-through voltage will not be reached.

But there are also some draw backs resulting from the by-pass diodes:

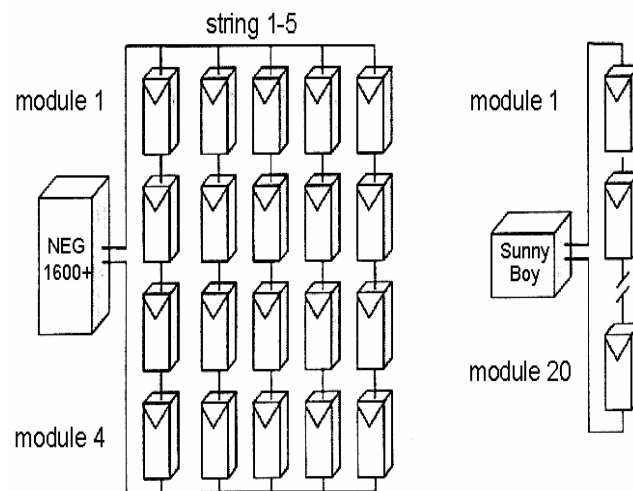
- higher cost for the module production and assembly problems of the by-pass diodes.
- losses in the by-pass diode in the case of shading
- matching problems between the solar inverter and the photovoltaic generator because of the second local power maximum might not be included in the range of operation of the inverter.

Two inverters were available for grid connected PV systems which were taylored to operate on different voltage levels. For the investigation we used two types of which the data are given in Table 1.

**Table 1:** Inverter parameters

Parameter	Type A	Type B
input voltage in V	54-98	125-500
input current in A	35 (max)	3-8
$U_{max}$ in V	110	500
nominal power in W	1740	1600

For the photovoltaic generator a number of 70 W modules were used and the circuit was designed to match with the inverter requirements [1]. The arrangement of the modules is shown in Fig. 1 and the details of the generators can be taken from Tables 2 and 3.

**Fig. 1:** Circuits of PV generator**Table 2:** PV Generator data

Inverter	Strings	Modules/String	Number of modules
Type A	5	4	20
Type B	1	20	20

**Table 3:** PV Generator details

Inverter	$P_n$ in W	$U_{MPP}$ in V	$I_{MPP}$ in A	$U_o$ in V	$I_{SC}$ in A	$U_{max}$ in V
Type A	1400	66.8	21	84.4	22.5	95.2
Type B	1400	334	4.2	422	4.5	476

### 2. MODELLING

The classical one-diode model of the solar cell is not sufficient to handle problems of shade on cells. Therefore the model was extended, now including also the negative section of the diode characteristic. The well known equation is modified to:

$$I = I_{photo} - I_S \left( \exp\left(\frac{U + I \cdot R_S}{m \cdot U_T}\right) - 1 \right) - \frac{U + I \cdot R_S}{R_P} - b(U + I \cdot R_S) \left( 1 - \frac{U + I \cdot R_S}{U_{Bt}} \right)^{-n} \tag{1}$$

with

$U_{bt}$	break through voltage (- 10 ... - 50 V)	$B$	correction factor
$n$	exponent (1 ... 10)	$I_S$	saturation current
$m$	diode factor	$U_T$	temperature voltage: $U_T = k \cdot T/e$
$R_S$	series resistor	$R_P$	parallel resistor
$U$	output voltage	$I$	output current

We measured the dark characteristic and realised that in the blocking state the voltage is often larger than 10 V. In combination with the resulting current the losses can be quite high. Fig. 2 shows the complete characteristic.

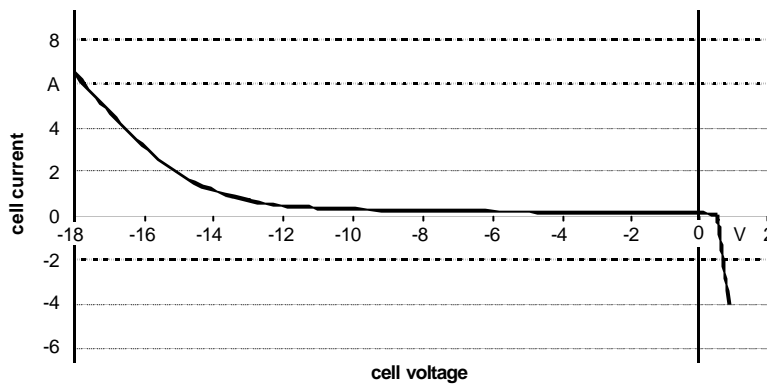


Fig. 2: Complete characteristic

The incomplete IU-characteristic of 35 cells under full insolation and one cell shaded with only 50 % of the insolation is shown in Fig. 3.

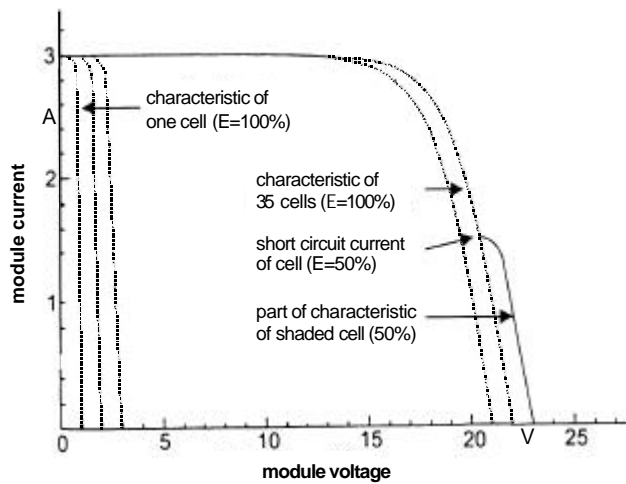


Fig. 3: Incomplete module characteristic

Taking into account the shaded area the final type of characteristic is given in Fig. 4. The power loss cannot be ignored.

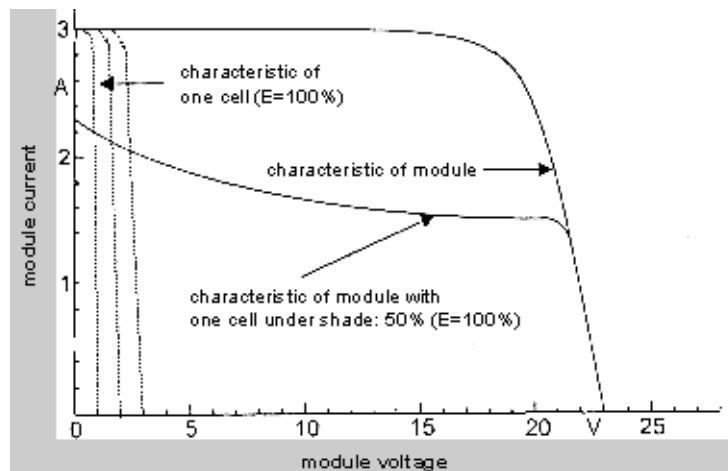


Fig. 4: Module characteristic with one cell shaded (50%)

What is the effect of by-pass diodes over 18 cells? Based on the by-pass diode characteristic we obtain a modified I-U-characteristic which is depicted in Fig. 5. Beside the simulation work also measurements were done for different levels of shade on cells of a module. From Fig. 5 it is already obvious that in this case we have a power versus voltage characteristic with two maximums.

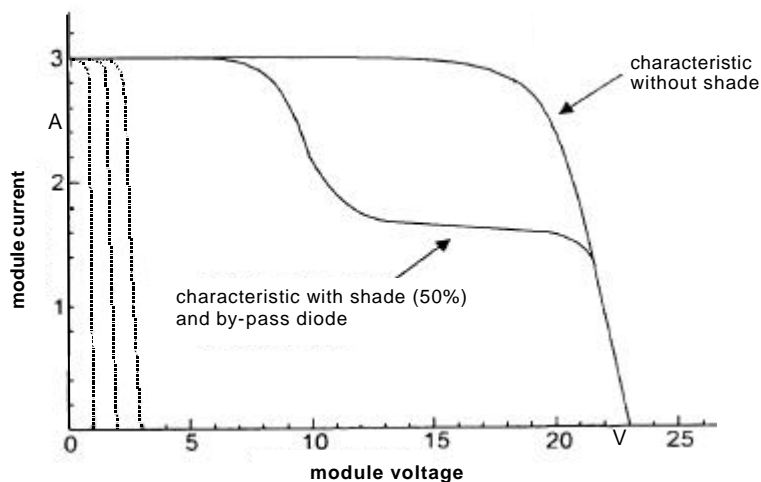


Fig. 5: Module characteristic with one cell shaded (50%) and two by-pass diodes

Fig. 6 and Fig. 7 give an example of measured characteristics showing that the first and second maximum can be found over a wide voltage range. The power at maximum power point (MPP) for unshaded conditions is about 53 W.

The power drops to 38 W in the case of 50% shaded area just for one cell. In the case of two cells and the same conditions the first maximum is at 20 W while the second is close to 33 W. A small shaded area results in a dramatic loss of power [2]

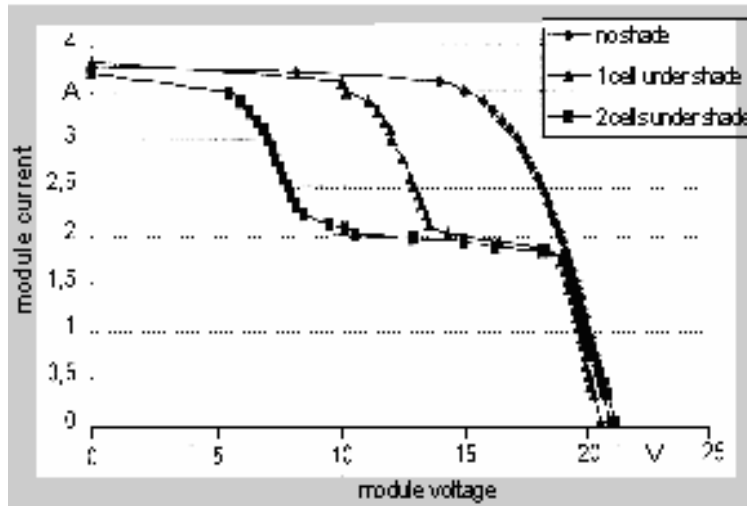


Fig. 6: Measured module characteristic

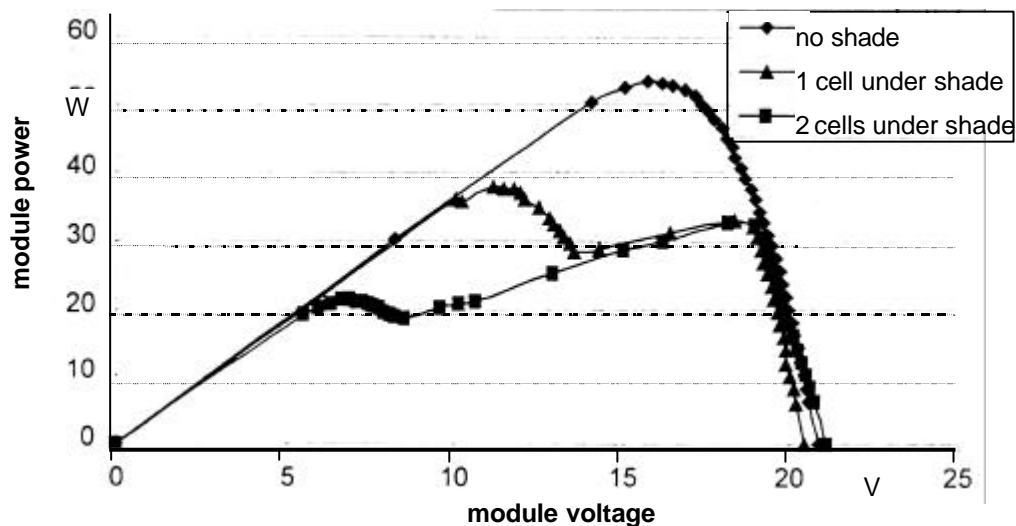


Fig. 7: Measured power versus voltage

### 3. GRID COUPLED PV SYSTEMS

Grid coupled PV systems are also characterised by the solar inverter, including the MPP tracker, between the grid and the module array. Before switching on the system the PV generator is in no-load mode. As soon as the inverter is feeding into the grid the voltage drops and approaches the MPP-voltage. Once the controller has reached that point only small oscillations around the MPP can be observed.

In the case of poor insolation and therefore modest currents the controller will provide a fixed voltage level below MPP voltage. If the voltage drops further, e.g. due to high ambient temperature or less effective cooling, below a set-point the inverter will cut off the grid and the PV generator is in no-load conditions again.

### 4. PATTERN OF SHADE

As a new parameter to describe the level of shading of a cell we used the following definition:

$$S_c = 1 - (E_{c,shaded} / E) \tag{2}$$

For an average insolation of  $700 \text{ W/m}^2$  on the shaded cell, we get for  $1000 \text{ W/m}^2$  on the unshaded cells a shade parameter of  $S_c = 0.3$ .

The effect of shade on the performance of a PV generator depends on influences such as:

- reduction of insolation (as average value)
- distribution of the shade on the PV generator (geometry of shade)
- modules with or without by-pass diodes
- circuit design of PV array (series connection, or strings in parallel).

Experimental investigations and simulations were done for a variety of pattern of shade, e.g. simulations were done for  $S_c = 0.3, 0.5$  and  $0.7$ .

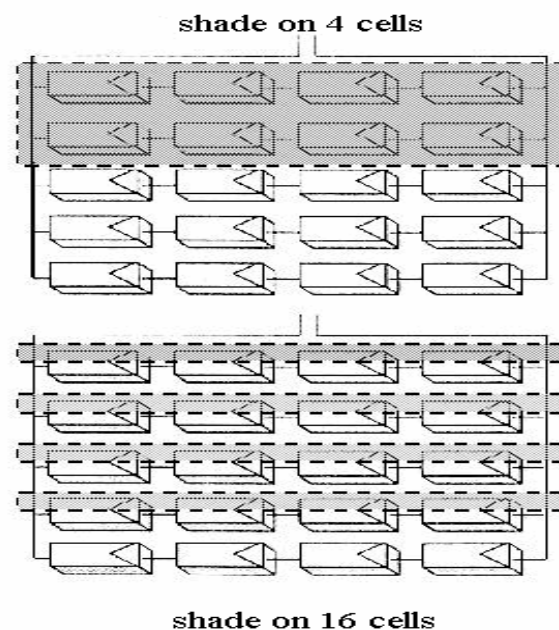


Fig. 8: Example of shade pattern

We focused on shade pattern on 4, 8, 12, and 16 cells for:

- a) single string of modules for inverter type B
- b) two strings for inverter type A
- c) four strings for inverter type A

An illustration example is given in Fig. 8.

Shade pattern b) was realised by shading a single cell under each of the by-pass diodes for one module and this was repeated for a specific number of modules.

For case c) all the four modules of a string had one cell shaded and this lay out was repeated for the other strings, as shown in Fig. 8.

## 5. POWER REDUCTION

For the series connection of the modules and inverter type B and  $S_c = 0.7$  we measured a loss of power of about 10 % when four cells were shaded. The losses increased to 59 % for 12 and 16 cells under shade.

For the five strings in parallel and inverter type A and again  $S_c = 0.7$ , but only four strings shaded we found interesting results. The lower MPP can reach 27 % of power losses while the upper MPP may show a reduction of 46 %. This can be observed when 12 or even 16 cells are shaded.

In addition voltage drops occur up to 50 % and also a voltage increase above  $U_{MPP}$  of about 20 % was found. The temperature influence was also analysed because beside the STC temperature of 25° C the voltage for - 10° C and + 60° C is of interest:

$$U_{MPP,\vartheta} = U_{MPP,STC} + (25 - \vartheta)RTC_V \quad (3)$$

For inverter type A the  $U_{MPP}$  will vary between 77.6 V (- 10°C) and 56.0 V (60°) and for inverter type B we calculated 388 V (- 10°C) and 280 V (60°C).

## 6. CONCLUSIONS

Beside insolation and temperature also the pattern of shade has a big influence on the position of maximum power point.

Shade pattern may result in two MPP's and the voltage  $U_{MPP}$  can increase above  $U_{MPP,STC}$  or drop below. However, the voltage  $U_{MPP}$  should always be within the range of operation of the inverter. The actual working point of the inverter is also a function of the shade distribution which will change with the position of the sun. If we switch on an already shaded PV system connected to an inverter the working point will be the upper MPP although this is not the real MPP.

If the MPP-voltage operation range is selected too narrow the lower MPP might be outside the range for higher temperature and shaded cells. In this case the controller will operate always with the upper MPP resulting in reduced energy yield.

## REFERENCES

- [1] SOLON AG, **Manual NEG 1600+** (1999)
- [2] V. Quaschnig, "*Simulation der Abschattungsverluste bei solarelektrischen Systemen*", Diss. TU Berlin, Verlag Dr. Köster (1996)