PARTIAL SHADINGS ON PV ARRAYS: BY-PASS DIODE BENEFITS ANALYSIS

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ABSTRACT: We present a methodology for the analysis and the evaluation of the electrical effects of partial shadings on a PV array. This methodology is namely developed in a pedagogic tool of the software PVsyst, which aims to explain how a shaded cell or group of cells behaves within a PV array. We use this tool for understanding the functions of the by-pass diodes, and quantify the array electrical losses in some typical situations, when one or several cells are shaded. We show that the electrical shading effect is dependent either on the length of the strings, and on the number of strings in parallel. This method should be applied for accurate shading calculations within the simulation process of PVsyst in a near future.

Keywords : Shading – Modelling - Simulation

1. INTRODUCTION

With the development of Integrated Photovoltaic Arrays in the built environment (BIPV), the shading loss evaluations become more and more important. But the shading losses effects are not intuitive. They have to be quantified using simulation software working in hourly or sub-hourly steps, along the whole year.

We distinguish two kinds of shadings on a PV plane: the "**far shadings**", which are supposed to act globally on the PV plane; and the "**near shadings**", which produce partial shades on the PV installation.

The "far shadings" situation may be defined by a simple "horizon" line. The obstacle is sufficiently far for considering that at a given time, the sun is or is not present on the field. The horizon line is supposed to be viewed in the same way from any point of the field. The simulation can estimate the exact time during which the sun is shining, and simply withdraw the beam component when it is under the horizon line. Most of the PV simulation software are treating the far shadings.

Shadings from near objects produce visible shades on the PV system. At a given time, we can define a "shading factor" as the fraction of the PV system effectively shaded. The calculation of the shading factor at any time, i.e. as a function of the sun's position, requires a full 3D representation of the PV field configuration and its surroundings. This is only performed by some few simulation tools.

Applying the "Shading factor" to the beam component allows the evaluation of the irradiance deficit on the PV plane; which we call "Linear shadings", because the effect is proportional to the shaded area.

But this is not representative of the real energy losses, as the electrical behaviour of the PV array is far from being linear: in a string of modules, the current of the weakest cell (the shaded cell) is influencing the current of the whole string of modules in series. The details of this complex behaviour are the subject of this paper.

Now in the PVsyst software (*Mermoud,* [5]), the user can split the PV field into rectangular areas, each rectangle covering about a whole string of modules. Then the program computes another shading factor "according to modules", supposing that when a rectangle is hit by a shade, the corresponding string becomes unproductive. The full simulation leads to a shading loss evaluation "according to modules", which should be an upper bound of the electrical shading effect. The real shading effect should lie between the "linear" loss and the loss "according to module". But we have no mean at the moment for determining where is the real loss between these bounds.

All these considerations apply to the beam component. For the diffuse part, we do the assumption that it is isotropic, i.e. that the same irandiance is coming from any direction of the sky (which is the case for example under covered weather). Then we may integrate the shading factor over all the sky directions "viewed" by the array, and we obtain a shading factor to be applied to the diffuse part. As this doesn't depend on the sun's position, this is a constant factor over the year. For this integration we can use the "linear" shading factor as the effects on the array will be diffuse.

We use a similar method for the estimation of the shading factor on the albedo part.

2. ELECTRICAL ANALYSIS

The electrical behaviour of a PV array with shaded parts has been studied in some particular cases (ref [1], [2]).

PVsyst provides a pedagogic tool for understanding the electrical behaviour of a PV array with shaded cells or groups of cells, useable when there are no intermediate interconnexions between strings.

Knowing the full I/V characteristics of one cell (with or without shading), we can add the voltages of each cell in series for obtaining the full I/V characteristics of one string. Then, for representing the characteristics of the whole array, we add the currents of the I/V curves of each string connected in parallel.

On the final shaded array characteristics we can now search the Maximum Power Point, and compare it with the unshaded array for determining the electrical loss. In some situations, there may be two maxima, so that the inverter algorithm may be mislead.

This process requires a full determination of the I/V characteristics, including toward negative voltages. In the usual quadrant this is given by the standard "one-diode" model available in PVsyst (ref [3], [4]).

For negative voltages we developed a simple model by measuring the reverse characteristics of one cell. This model supposes a quadratic increase of the "forced"

current with the voltage, until a breakdown value (Zener avalanche) which is never reached in practice, because the cell is destroyed by the temperature due to the power consumption. Fortunately the accuracy of this model is not crucial for the determination of the array's behaviour. By the way the reverse characteristics is very unstable as strongly dependent on the cell's temperature.

3. HOT SPOT and BY-PASS DIODES

Let us first analyze the behaviour of one only module, with one shaded cell. On fig 1, we draw the characteristics of one cell shaded at 80%. As the irradiance is reduced to 20%, the cell's Isc is 20% of the full Isc. Now the reverse characteristics begins at Isc current level, and increases quadratically when the reverse voltage increases, absorbing energy from the external circuit. The resulting cell temperature is evaluated.
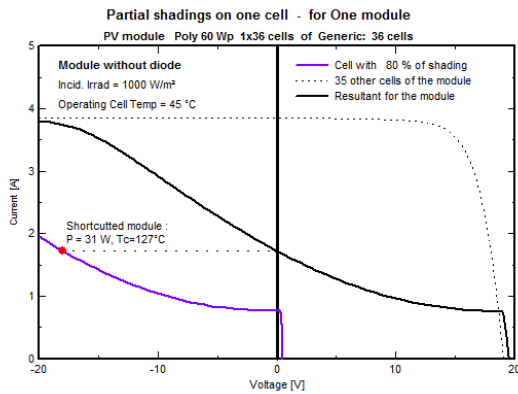

Fig 1. – PV module with one shaded cell, without diode

The dotted line shows the 35 other cells of the module. The resulting I/V curve for the shaded module is the sum in voltage. When the module is in short-circuit (about 1.8A here), the shaded cell absorbs the power produced by the rest of the module (the voltages are exactly opposite), reaching about 127°C.

Now, once integrated in an array, the operating point (MPP) of the array may force a current largely higher than the short-circuit point of the module, leading to prohibitive powers on the cell. This is the "Hot-spot" phenomena.

In order to protect the cell, manufacturers have to put anti-parallel ("by-pass") diodes on the modules, which will derive the current when the voltage becomes negative.

One diode over the module would no be sufficient, limiting the power at around 31W on the cell, as on fig. 1. This module requires to be splitted into 2 sub-modules, each protected by one by-pass diode. As shown on the fig. 2, this will limit the cell's power consumption to a safe value of 10W. The diode of this sub-module will act from about 1A, and the Pmpp of the module will be enhanced.

Therefore the first function of the by-pass diodes is the protection of the module against Hot-Spot and destruction of cells. As a general rule, one diode is required for about 18 to 24 cells.
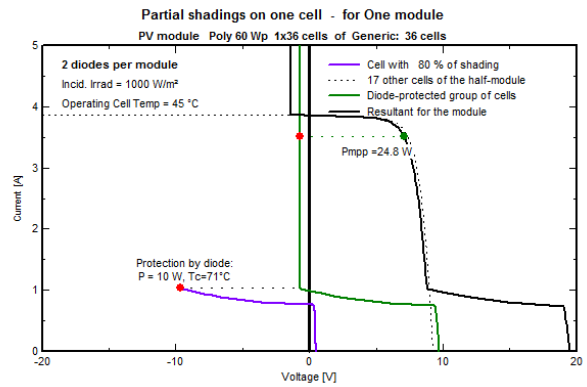

Fig 2. – PV module protected by 2 by-pass diodes

We can notice that this is a worst case, but not meaningless (for example a dead leaf). If there are two shaded cells in the same sub-module, they will share the power to be dissipated, removing the problem.

The second function of the by-pass diode is to reduce the reverse voltage across the sub-module, therefore limiting the shading voltage drop within the string to the normal voltage of one sub-module (-0.7V).
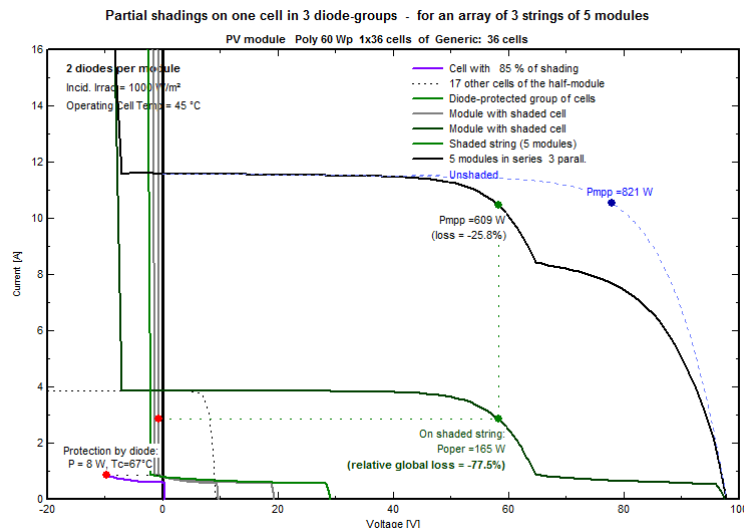

Fig 3. Behaviour of a shaded array of 3 strings of 5 modules

Thin film modules are usually not equipped with by-pass diodes. On one hand this would require to have a connexion at the mid-point, and on the other hand it would be difficult to shade a full cell (10mm x length of the module). Therefore the problematics of partial shadings on thin film modules is quite different, provided that the shades are not aligned along the cells.

4. ARRAY ELECTRICAL BEHAVIOUR

As an example of the method, the figure 3 illustrates an array of 3 strings of 5 modules in series, modules equipped with 2 by-pass diodes each.

3 cells are shaded at 85% in 3 different sub-modules. These 3 sub-modules (Vmpp about 10V each) give the flat I/V characteristics at low current. To these shaded sub-modules, we add (in voltage) the rest of the 7 remaining unshaded sub-modules, which gives the full I/V characteristics of this string.

Finally we add (in current) the 2 unshaded strings and obtain the full characteristics of this shaded array.

Now when operating at the MPP, the power converter will fix the operating voltage of the array.

As the strings are connected in parallel, this operating voltage is common to all strings, and this will fix the operating current of the shaded string. We observe that without protection diodes, this current would lie in a dangerous zone for the shaded cells.

We can point out here the highly non-linear properties of the electrical shading effects. The shades on these 3 cells (among the 540 cells of the array) represents less than 0.5% of irradiance deficit ("linear" shading). But they induce an electrical loss of 26% on the whole array production !

5. QUANTITATIVE LOSS EVALUATION

The pedagogic tool available in the standard PVsyst software, may be used for the evaluation of the shading effects in some particular situations. But the full shading electrical loss over a period cannot be appreciated intuitively – even by experts – without a complete hourly simulation over this period.

5.1. Several shaded cells in a same sub-module

Remember that we call "sub-module" a cell's array protected by one by-pass diode. For example our 36-cells module, protected by 2 by-pass diodes, is made of 2 sub-modules of 18 cells each.

Now when one or several cells are shaded in a single sub-module, the electrical loss is identical as soon as you have 3 or 4 sub-modules in series; because in these cases the current is high, so that only the reverse diode voltage is concerned. This means that within an array, we only have to evaluate the number of sub-modules affected by a shade. This will simplify a little bit the full calculation during the simulation process.

5.2. Effect of one-only shaded cell in an array

On the figure 4, we reported the loss due to only one shaded cell (or group of cells in a sub-module), as a function of the number of modules in series.
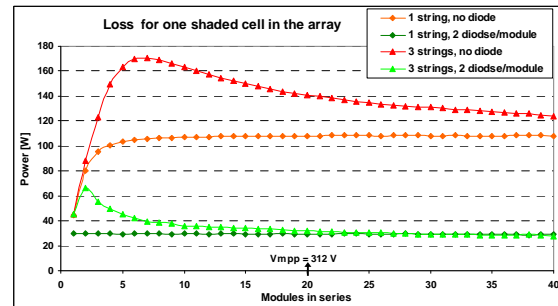
Fig 4. Energy loss due to one shaded cell

One module gives 55 W under 1000 W/m² and 45°C. For 85% shading on one cell, we can see that with by-pass diodes, the loss is limited to about the production of one sub-module (29W). Without diodes, the loss would be 2 times the module production; but this is not realistic because the shaded cell would be destroyed.

With one only string, the loss is stable whatever the number of modules in series. But when there are other strings in parallel, the shaded cell distorts the array I/V characteristics and displaces the MPP, resulting in an additional loss in the other strings production (but not more than the production of one module). This effect vanishes over 15-20 modules in series (i.e. Vmpp over 200 to 300V).

Therefore the assertion sometimes claimed that when one module is shaded, the whole string becomes inactive is not true. The power loss remains of the order of the production of one sub-module (less than 3% for 20 modules in series, but corresponding to 0.1% of irradiance deficit !).

As the absolute loss is stable, the relative loss (expressed in %) diminishes with the length of the strings. When several strings are present, the loss is also enhanced by the bump observed up to 10 modules in series.

5.3. Effect of several shaded sub-modules in an array

But this particular case should not hide the problem. When several sub-modules are hit by the shade, the loss increases rapidly.

The figure 5 shows the energy loss, in terms of % by respect to the normal production of the shaded string, as a function of the number of shaded sub-modules.

The "linear loss" represents the irradiance deficit, when each cell of each shaded sub-module is fully shaded (i.e. receives 15% of irradiance, the diffuse residue).

With a one string array, the over-loss by respect to the linear case (i.e. the "electrical" loss) is about 29% until the elbow.

But we observe that this loss significantly increases when the array has several strings. With ten strings, it attains 2 to 3.5 times the linear loss before the elbow.

The analysing tool of PVsyst allows to easily understand this. The shaded string displaces the MPP operating point of the entire array, so that the adjacent strings don't work at their own MPP anymore. This is obviously not the case when there is only one string.

Therefore the usual hypothesis that the strings are independent regarding the shading effects is not true.
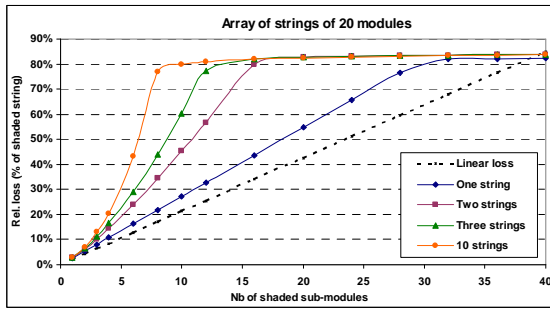
Fig 5. Relative loss, function of shaded sub-modules number.

5.4. Inverter uncertainties

The plateau on the curves corresponds to situations where the second maximum (at higher voltages) becomes predominant. But the correct behaviour of the inverter is not ensured when crossing this situation: the MPP tracker looks for near voltages during its continuous optimizations, and may not notice the presence of this second maximum. In these cases the "electrical" loss will follow the increasing curve, and may overcome the loss of one only string.

This phenomenon cannot be taken into account by the simulation program, as it depends on the MPPT algorithm, as well as on the "history" of the apparition of the shade.
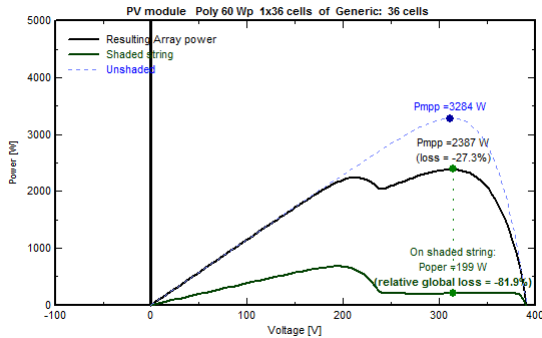

Fig 6. Power conditions near to the plateau

5.5. PVsyst limit "according to modules strings"

In PVsyst, the upper limit calculation named "Shadings according to module strings" - which supposes that when one string is hit by a shade the whole string becomes inactive - would correspond on the figure 5 to a constant loss of 85%, whatever the number of shaded sub-modules.

We can observe that with arrays constituted of one only string, we are relatively far from this limit. But with several strings the real electrical effect approaches this limit (the 60-80% value proposed by the software for the "Fraction of electrical effect" is probably realistic).

For very "organized" shade situations like shed's mutual shadings – where the shade concerns all sub-modules at a time – we are on the right of this graph and the real situation is very close to the limit. In these cases the "Fraction of electrical effect" approaches indeed 100%.

6. INTRODUCTION IN THE SIMULATION

This gives indications for some particular cases. The next step is to include this calculation within the simulation process.

6.1. Module layout

This requires that the position of each module is geometrically well-defined in the field, as well as its attribution to a given string (and even a given inverter or MPPT input). The module layout and string attribution have been introduced in the version 5.2 of PVsyst.

Now we have still to do the relation with the 3D shading part, for the calculation of the shading state of each sub-module. After that, at each time step the simulation will be able to calculate the full electrical behaviour of each sub-array connected to each MPPT input.

This calculation will only be necessary when there is a beam contribution to the incident irradiance. The shading effect on the diffuse part remains a constant attenuation factor computed once by an integral over the part of sky "seen" by the PV array.

6.2. Series protection diodes in strings

We can mention that a full shading (100%) cannot arise in the reality. There is always a residual irradiance due to the diffuse component, which is never less than 12 to 15% of the full irradiance. This implies that the maximum voltage of each string is not affected by the shadings, as seen on figure 3.

Then, when designing a PV array, a usual practice was to put a series diode in each string, for avoiding reverse currents flows from not-shaded strings into shaded ones. Due to the above assertion, this is quite useless, as the shaded string voltage will always be over the operating point, and therefore cannot be reverse-biased by the neighbour strings.

7. CONCLUSION

Near shading loss on PV systems remain a difficult uncertainty when evaluating the yield of a PV system. Some simulation tools calculate losses based on the irradiance deficit only. PVsyst gives an upper limit of the electrical effect, according to a rough string layout.

We propose here a model which allows the detailed calculation of the "electrical" shading losses. We can already use this tool for understanding some principles, namely the role of the by-pass diodes, the effect of one cell shading (which withdraws the production of one sub-module), or the effect of several shaded sub-modules. A surprising observation is that the shadings on different strings are not independent, and that one only string behaves much better than arrays of several strings.

This methodology has still to be implemented in the general simulation process for the evaluation of the real energy losses in any given PV system, over any period. This should be realized in PVsyst by the end of this year.

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