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Hot-spot mitigation in PV arrays with distributed MPPT (DMPPT)

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Abstract

A lack of maintenance in PV systems can cause hot-spots due to localized or irregular dirt, causing permanent losses and reducing the reliability of the system. By-pass diodes were introduced to lessen this problem although they do not eliminate it completely, as recent literature has shown. This paper analyzes the use of distributed MPPT (DMPPT) in relation to mitigation of hot-spot problems. A full analysis is performed, including simulations of *I–V* curves under different shading situations and an in-field analysis. The results show that DMPPT is less prone to hot-spots than central MPPT in a different range of shadows depending on the module type.

Keywords: Hot-spot; DMPPT; Shadow; Localized dirt; Power optimizer; Micro-inverter

1. Introduction

Hot spots are a well-known phenomenon, described as early as 1969 (Blake and Hanson, 1969), still present in photovoltaic (PV) arrays (Lorenzo et al., 2013; Muñoz et al., 2008; Sánchez-Friera et al., 2011; TamizhMani, 2010) and considered a cause of degradation of PV modules (Munoz et al., 2011; Ndiaye et al., 2013). They occur when a cell, or group of cells, operates at reverse-bias, dissipating power instead of delivering it and, therefore, operating at abnormally high temperatures. Cells exposed to higher temperatures will degrade at a higher rate than others and, if operation at high temperatures occurs during a prolonged time, it can cause irreparable damage to the solar cell; forcing it to permanently work in reverse bias and rendering useless the rest of the cells under the same by-pass diode. Even if the cell does not result damaged, the exposure to high temperatures will result in a faster degradation of the material used for the module's encapsulation (Oreski and Wallner, 2005, 2009), reducing the radiation that reaches the cell. PV modules should be resistant to hot-spot problems and the international standard IEC-61215 describes the procedure for hot-spot resistance testing (IEC, 2005).

One of the functions of by-pass diodes is to limit hot-spot effects to a minimum, however, even with their use, hot-spots can still occur in PV modules due to localized or irregular dirt. In (Lorenzo et al., 2013), differences of up to 20 °C between shaded cells and non-shaded cells were observed, caused by irregular dirt over the modules like that of Fig. 1(c) and (d), and a study from the TÜV (TamizhMani, 2010) found a 10% failure rate in the hot-spot resistance test of 1220 c-Si modules during the 2007–2009 period. The study also shows an increased trend with respect to previous periods.

This effect is worst when only one cell is partially shaded since it alone has to dissipate the power of the rest of cells protected by the same by-pass diode; the case of localized dirt, bird droppings, leaves, etc. Fig. 1(a) shows an example of a permanent hot-spot in a real PV system with modules with by-pass diodes. Fig. 1(b) shows a large bird-dropping with a hot-spot under it (also in modules with by-pass diodes) and Fig. 1(c) and (d) show other possible causes for hot-spots.

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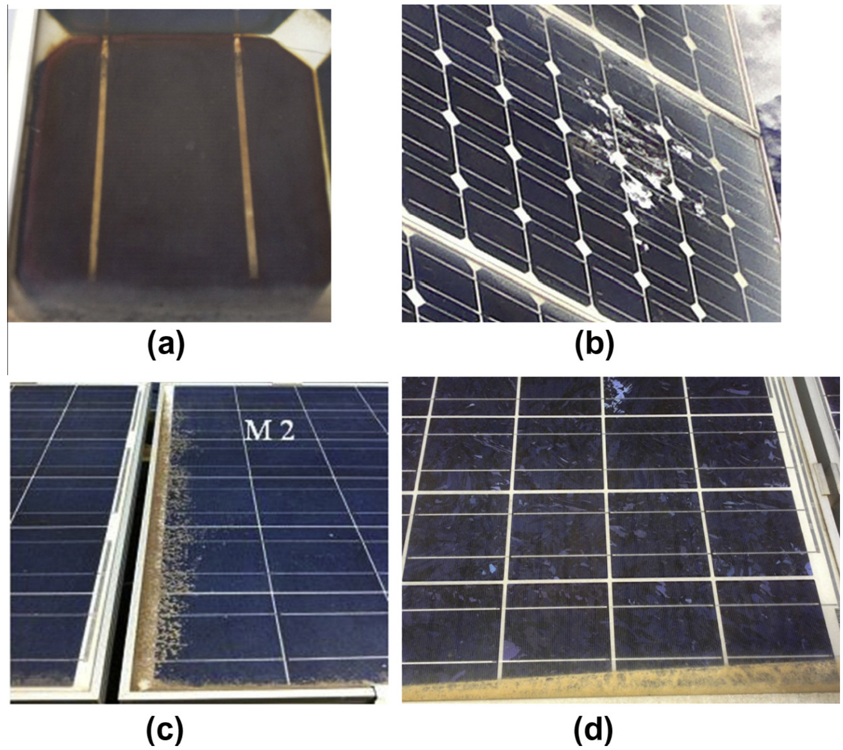

Fig. 1. Examples of hot-spots and their possible causes. Figure (a) shows a permanent hot-spot from a real PV system with by-pass diodes. Figure (b) shows a large bird dropping which does not wash away after heavy rain and that has caused a hot-spot. Figures (c) and (d) show irregular dirt patches which could lead to hot-spots like in Lorenzo et al. (2013).

This paper shows how the use of distributed maximum power point tracking (DMPPT), although initially intended for mitigating losses due to shading and mismatch (Orduz et al., 2013), can also be used to mitigate the hot-spot problem in PV arrays. This is especially important in PV systems in climates with little rain or systems with less maintenance, like small rooftop PV systems, being them more prone to hot-spot problems. In addition, losing a module, or part of a module, due to a hot-spot is more significant in a small 3 kW system than in a large 30 MW PV plant and its replacement more problematic since there are usually no full-time employers on-site for small systems.

In the following sections, a theoretical analysis comparing hot-spot possibilities in DMPPT and centralized maximum power point tracking (MPPT) systems is presented and experimentally verified.

2. Theoretical analysis

All explanations given in this section assume that the MPPT algorithms of both central inverters and DMPPT systems always find the maximum power point (MPP), even under shading situations. This is a reasonable assumption considering modern inverters and it has been verified in a commercial power optimizer. The results of Section 3 are also in agreement with this assumption.

2.1. Theory

When a solar cell is partially shaded, generally, two situations can occur:

(a) the shaded cell works in reverse bias and matches the current of the non-shaded cells
(b) the non-shaded cells reduce their current to match that of the shaded cell's.

Each of these possibilities creates a local MPP and the MPPT algorithm polarizes the array or module at the global MPP. In turn, this depends on the number of diode blocks[1] for which the MPPT algorithm is applied and the amount of shade applied to the cell.

As an example we can consider a ten module PV generator with three by-pass diodes per module. If a cell is shaded by 20%, and the rest of the cells lower their current, a 20% power loss occurs in both a DMPPT system and a classic MPPT system. On the other hand, if the shaded cell is in reverse bias, and its negative voltage is enough to polarize the diode in forward bias, the power from a whole diode block is lost. In a central MPPT system, the MPPT

[1] A diode block is considered as the block of cells protected by one diode. A module with three by-pass diodes will have three diode blocks and a PV generator with ten of these modules will have 30.

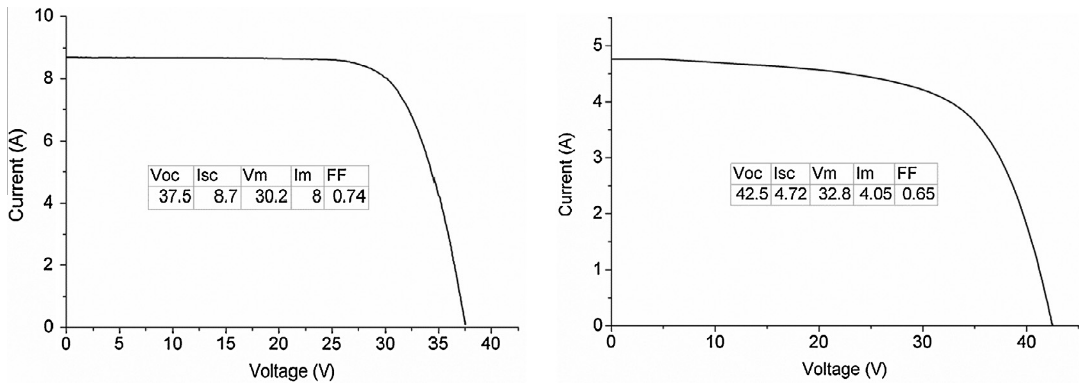

Fig. 2. Real I–V curves of the modules used for the simulations and their main characteristics. Module-1 (left) and Module-2 (right).

algorithm will detect a loss of approximately 1/30 (one diode block out of 30) of the power and with DMPPT the algorithm detects a power loss of approximately 1/3[2], since it is now at module level and there are three by-pass diodes. With DMPPT the algorithm will "choose" to reduce the current of the non-shaded cells while with central MPPT, the algorithm will "choose" to lose the power from a diode block, meaning that the shaded cell will work in reverse bias with little shading in central MPPT but a larger shade is needed for this with DMPPT.

However, further considerations should be taken:

(1) the shaded cell has some margin until it works in reverse bias: from I_M to I_{SC}, related to the shunt or parallel resistance, R_P.
(2) If the non-shaded cells reduce their current they are also increasing their voltage, so the power lost is not exactly equal to the current reduction and it depends on the slope of the I–V curve from V_M to V_{OC}, which is related to the series resistance, R_S, of the cells.
(3) The reverse characteristics of the shaded cell(s) will affect the power lost by the diode block when the shaded cell(s) work(s) in reverse bias and, therefore, the decision of the MPPT algorithm.

In order to analyze all these effects a series of simulations have been performed with different PV modules and with cells of different reverse characteristics.

2.2. Simulations

These simulations have been performed with the real I–V curves of two different PV modules. Module-1 is made up of 60 mono-crystalline solar cells in series and three by-pass diodes and Module-2 of 72 poly-crystalline solar cells in series and four by-pass diodes. For each module type, ten modules are connected in series for the central MPPT simulations.

[2] Note that in the global system the power loss in the same in both systems. 1/3 in one module out of ten is the same as 1/30.

Both modules' I–V curves and their characteristic values are presented in Fig. 2. Module-2 is the module that is used in the "in-field analysis" in section 0. From the curves it can be seen that Module-2 has a lower fill factor (FF), having both a lower R_p and a higher R_s. These factors will influence the results of the simulations as seen further on in this same section.

The shaded cell's reverse I–V curve has been modeled with Eq. 1, proposed in (Alonso-García and Ruíz, 2006).

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

where B_e is a non-dimensional cuasi-constant parameter with value ≈ 3, V_b is the breakdown voltage, ϕ_T is the built-in junction voltage (not to be used as an adjustable parameter, using a typical value of $\phi_T = 0.85$ for silicon cells of unknown junction structure.), and G_p is the shunt conductance. The addition of the parabolic term c ($c < 0$) is used in cases where the linear fitting is not sufficient. This equation is valid for different types of cells and it can be adapted to each cell by changing V_b and c.

Large differences have been found in the reverse characteristics of solar cells in the same module (Alonso-García et al., 2006). These differences will affect the negative voltage at which each cell is biased and, therefore, the power lost by the system as well as whether the MPP is located at a point where the shaded cell is in reverse bias or not. For the two previous modules, the reverse characteristics of two cells have been obtained by shading these cells in different percentages, measuring the I–V curve of the module and then matching the simulated I–V curve with the measured one. This method was already presented and validated in (Solórzano-Moral et al., 2013), using the same module as Module-1. The values obtained are: $V_B = -27$ V and $c = -0.0055$ for "Module 1" and $V_B = -6.5$ V and $c = -0.005$ for "Module 2". Both modules present clear differences in their I–V curves and in the reverse characteristics of their cells. Simulations have been carried out considering these differences and quite different results are obtained for each case.

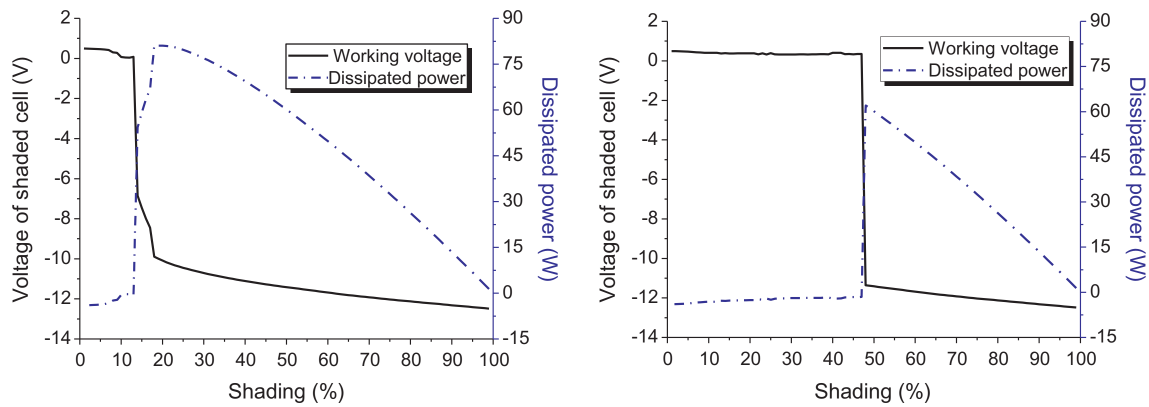

Fig. 3. Comparison of the working voltage (solid line) and the power dissipated (dashed line) of the shaded cell in Module-1 in a ten module system for central MPPT (left) and DMPPT (right). With central MPPT the switch from forward to reverse bias is at 12% shade while with DMPPT it is at 48% shade.

The procedure for the simulations is to consider all cells from both modules to be equal, obtaining its *I–V* curve by simply dividing the voltage of the module's *I–V* curve by the number of cells in series. To the *I–V* curve of each cell, its *I–V* curve in reverse bias, obtained with equation 1, is added. Then, the shaded cell's current is decreased by the same percentage as the amount of shading applied and all the cells are added in series considering the diodes in the modules and the *I–V* curve of the shaded module is obtained. By adding in series the *I–V* curves of ten modules, the *I–V* curve of the generator is obtained.

For finding the shaded cell's working point, V_{m_c} and I_{m_c}, first the MPP of the module or generator (for DMPPT and central MPPT respectively) is obtained. We then consider that the current of the generator's MPP is the same as that of the shaded cell and we find the working voltage of the shaded cell. If this voltage is not negatively large enough to forward bias the diode (as is the case with Module-2), this remains as the shaded cell's working point. If it is negatively large enough (Module-1), then the diode block is isolated and considered to have a working voltage of −0.6 V. Then, considering that the current through the shaded cell and the non-shaded cells under the same diode must be the same and that their voltages must add -0.6 V, the working point of the shaded cell is obtained.

Figs. 3 and 4 show the working voltage of the shaded cell and its dissipated power as a function of the amount of shading for Module-1 and Module-2 respectively. It can be observed how there is an initial region where the shaded cell works in forward bias in both systems, being it close to 12% for Module-1 and 17% for Module-2. In both cases, the MPP is found at a point where I_M is slightly reduced, expanding the range until the shaded cell works in reverse bias (note that the ratio between I_{SC} and I_M is ~8% and 14% respectively).

In both modules, after the initial region, 12% and 17% shade respectively, the cells in the central MPPT system start working in reverse bias and start to dissipate power. In the case of Module-1, the cell starts working in reverse-bias increasing its negative voltage and the dissipated power until it reaches a high enough negative voltage that places the diode in forward bias, at approximately −10.5 V. At this point the diode limits the power dissipated by the shaded cell, accomplishing its function. Since the negative voltage at which the shaded cell is biased remains almost constant, due to the −0.6 V imposed by the diode, as the shade increases its working current decreases[3] and therefore the dissipated power also decreases, reaching a value of 0 W at 100% shade. In the case of Module-2, since the maximum negative voltage of the shaded cell is not high enough to forward bias the diode, the dissipated power is always increasing and the working voltage always negatively increases until almost its maximum −6.5 V (Fig. 4).

In Module-1, from 12% to 48% the cell in the DMPPT system keeps on working in forward bias and does not dissipate any power, being, therefore, hot-spot risk free (Fig. 3-right).

It should be noted that this range of shade is for which the cell in the central MPPT system dissipates the most power (see Fig. 3), because the by-pass diode works progressively in reducing the dissipated power. So, in this case, not only does the system with DMPPT eliminate a shade range of possible hot-spots but it eliminates the worst range. This occurs in modules with cells that have large breakdown voltages or high shunt resistances.

From 48% onwards there is no difference in using central MPPT or DMPPT.

In Module-2, due to the difference in reverse characteristics of the shaded cell and to the larger number of by-pass diodes the range for which the shaded cell in the DMPPT system keeps on working in forward bias is much lower, from 17% to 28%. In addition, because the shaded cell's breakdown voltage is not high enough to polarize the by-pass diode in forward-bias, it never works in reducing the

[3] The lower current causes the non-shaded cells to slightly increase their voltage which in turn slightly increases the negative voltage of the shaded cell, from −10.5V to −12V approximately.

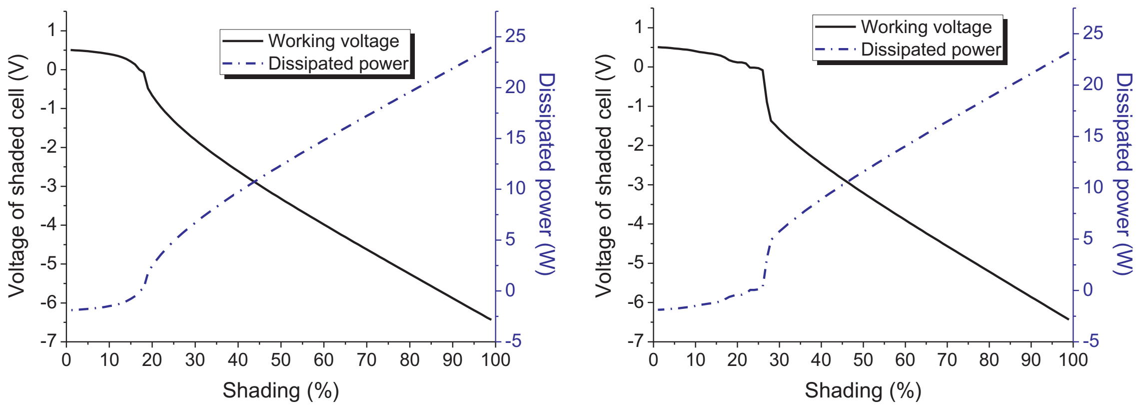

Fig. 4. Comparison of the working voltage (solid line) and power dissipated (dashed line) of the shaded cell in Module-2 in a ten module system for central MPPT (left) and DMPPT (right). With central MPPT the switch from forward to reverse bias is at 17% shade while with DMPPT it is at 28% shade.

Table 1
Maximum possible shade over one cell while it continues to work in forward bias.

	Maximum Shade	
	MPPT (%)	DMPPT (%)
Mod-1, Vb = −6.5 V, diodes = 3	8	19
Mod-1, Vb = −27 V, diodes = 2	12	62
Mod-1, Vb = −27 V, diodes = 4	12	40
Mod-2, Vb = −27 V, diodes = 4	20	47
Mod-2, Vb = −27 V, diodes = 3	20	55
Mod-2, Vb = −6.5 V, diodes = 3	17	27
Mod-2, Vb = −27 V, diodes = 2	20	66

dissipated power, being it always incremental, as opposed to the previous case. Also, because the V_b of the shaded cell is lower, the maximum dissipated power is lower than the case for Module-1, although this is not always synonymous to dissipating less heat as shown in (Alonso-García et al., 2003] and further experiments should be undertaken in this area.

Further simulations were conducted mixing the characteristics of both modules and adding new supposals, showing the results in Table 1. The table shows the percentage that a cell can be shaded before working in reverse bias for central MPPT and DMPPT systems. After these percentages of shade, the cell will work in reverse bias in both systems. It can be seen that in all cases the maximum shading that a cell can handle before working in reverse bias is higher in DMPPT systems. Having an shadow range where the shaded cell or cells do not work in reverse bias could solve hot-spot problems like those identified in (Lorenzo et al., 2013).

From the previous results and those shown in Table 1, it can be concluded that DMPPT is more beneficial against hot-spot problems in modules with a lower number of by-pass diodes and with a lower R_S as is the case with Module-1 (see Mod-1, Vb = −6.5 V, diodes = 3 vs Mod-2, Vb = -6.5 V, diodes = 3), as well as in cells with higher breakdown voltages. A lower R_P means that more shade is needed for the cell to work in reverse bias, in both central MPPT and DMPPT.

This, however, does not necessarily mean that fewer diodes should be used in PV modules or that cells should be manufactured with lower FFs. The first point could be valid but it should be further investigated and the second point will cause a loss in efficiency which generally is worse than having a hot-spot. The second point could be valid when a very robust system is preferred over an efficient one.

3. In field analysis

The experimental verification has been conducted at the rooftop of the Institut National de l'Energie Solaire (INES) in Chambery, France, at midday and in the month of February 2013. The string used for the tests consists of ten PV modules of the same model as Module-2 used in the simulations. Two different experiments were carried out:

(a) The string was connected to an inverter with a centralized MPPT and a solar cell in one of the ten modules shaded at different percentages. At each shading step, module voltage measurements and thermo-graphic images were recorded.
(b) The string was connected in a DMPPT system (each module to a power optimizer) and the same solar cell was shaded with the same pattern as before. Again, module voltage measurements and thermo-graphic images were recorded.

During the experiment the shaded cell was monitored until it reached a stable temperature value, considered as the maximum value and *I–V* curves were recorded. During each shade step the cell was given enough time to cool down to the temperature of the non-shaded cell and the *I–V* curves were compared to those of the simulations with good agreement.

Table 2 shows the working voltage (corrected in temperature) of the shaded module with central MPPT and DMPPT and the temperature difference between the shaded cell and the non-shaded cells. The results agree with what was exposed in the theory, showing that the shaded

Table 2
Corrected working voltage of the shaded module and temperature difference between the shaded cell and the non-shaded cells, with central MPPT and DMPPT.

Shading (%)	MPPT		DMPPT	
	V_{mod}	ΔT (°C)	V_{mod}	ΔT
0	32.5	0	32.5	0
10	33	2	33	0
20	31	18	33.5	1
25	30	18	35	1.9
40	29.4	19	29.7	2
50	28.3	20	28.5	19
75	28.1	20	28.2	20
90	27.1	19	27.5	20

cell does not heat up more than the non-shaded cell until over 25% shading, that the non-shaded cells increase their voltage when shading is applied (the current is, therefore, reduced) and also shows an approximate 5–5.5 V drop in the module at 90% shade.

For the DMPPT system there are shades where a temperature difference is noticed although the shaded cell is not in reverse bias. However, it is a small difference, 1–2 °C, which can be considered negligible. It could however be because the same amount of current is passing through a smaller area of cell than in the non-shaded cells. Although the dissipated power by the shaded cell increases as the shade increases, no significant increase in temperature difference was observed. For all shading percentages the temperature difference was practically the same. This could possibly be because of the low breakdown voltage of this cell in particular.

Figs. 5 and 6 show thermo-graphic images for 25% and 50% shade with and without DMPPT. It can be seen that for 25% shade the cell in the DMPPT system is not hotter than the other cells. However, with 50% shade, the cells in both systems are heated by practically the same amount. Although the temperatures are not very high, it should be noted that the measurements were taken in February in the French Alps and that these temperatures will be much higher in PV systems in southern Europe during the summer or other warm locations.

4. Conclusions

The effect of partial shading over one cell of a PV generator with central MPPT and DMPPT has been analyzed theoretically for modules with different characteristics and validated experimentally with one of the module types used for the simulations. The results show three different shading areas.

There is an initial area in which the shaded cell is not affected by hot-spots in either system. This depends on the difference between I_{SC} and I_M and, in turn, on the R_P.

A second area exists where central MPPT systems are affected by hot-spots and DMPPT systems are not. This area depends on the reverse characteristics of the shaded cell (mainly the breakdown voltage), the number of by-pass diodes and the R_S. This area is larger for modules with a lower number of by-pass diodes and with a lower R_S, as well as in cells with higher breakdown voltages. In one of the examples presented with real modules it ranges from

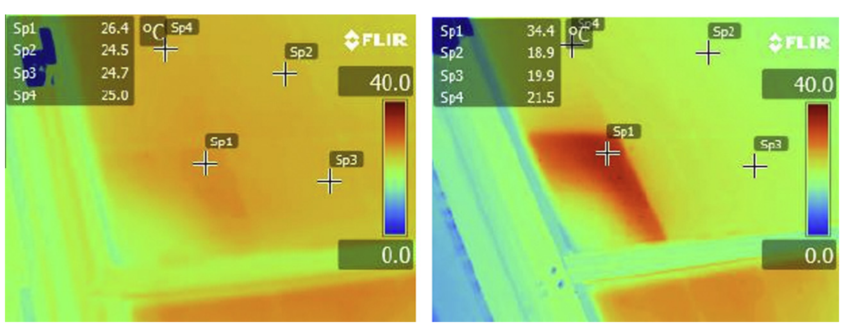

Fig. 5. Thermographic images of shading over 25% of one cell for DMPPT (left) and central MPPT (right).

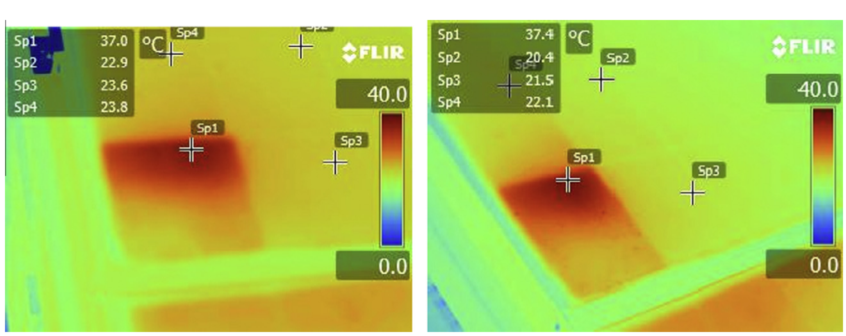

Fig. 6. Thermographic images of shading over 50% of one cell for DMPPT (left) and central MPPT (right).

12% to 48%, meaning that cells of this module can handle up to 48% shade before working in reverse bias. And, in one of the simulations with supposed modules it goes up to 66%. In addition, for shaded cells with high breakdown voltages, it is in this area of shade where the power that must be dissipated by the shaded cell in a central MPPT system is the highest, being it avoided in DMPPT systems.

Finally there is a third area where both systems are equally exposed to being affected by hot-spots and where the effect over the shaded cell is the same in both systems. In this area DMPPT has no benefit over central MPPT.

It has been shown that, in general, DMPPT systems are less prone to hot-spots, increasing the system's reliability and avoiding possible hot-spots in real PV systems like those pointed out by Lorenzo et al. (2013). This is especially interesting for PV systems with little or difficult maintenance, like small rooftop PV systems (DMPPT's natural market).

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References

Alonso-García, M.C., Ruíz, J.M., 2006. Analysis and modelling the reverse characteristic of photovoltaic cells. Sol. Energy Mater. Sol. Cells 90 (7–8), 1105–1120.

Alonso-García, M.C. et al., 2003. Thermal and electrical effects caused by outdoor hot-spot testing in associations of photovoltaic cells. Prog. Photovoltaics: Res. Appl. 11 (5), 293–307.

Alonso-García, M.C. et al., 2006. Experimental study of mismatch and shading effects in the *I–V* characteristic of a photovoltaic module. Sol. Energy Mater. Sol. Cells 90 (3), 329–340.

Blake, F., Hanson, K., 1969. The hot-spot failure mode for solar arrays. In: fourth Intersociety Energy Conversion Engineering conference. Washington DC, pp. 575–581.

IEC, 2005. Crystalline Silicon Terrestrial Photovoltaic (PV) Modules. Design Qualification and Type Approval, in IEC 61215. IEC Central Office, Geneva, Switzerland.

Lorenzo, E. et al., 2013. Dust effects on PV array performance: in-field observations with non-uniform patterns. Prog. Photovolt: Res. Appl. http://dx.doi.org/10.1002/pip.2348.

Muñoz, J. et al., 2008. An investigation into hot-spots in two large grid-connected PV plants. Prog. Photovoltaics: Res. Appl. 16 (8), 693–701.

Munoz, M.A. et al., 2011. Early degradation of silicon PV modules and guaranty conditions. Sol. Energy 85 (9), 2264–2274.

Ndiaye, A. et al., 2013. Degradations of silicon photovoltaic modules: A literature review. Sol. Energy 96, 140–151.

Orduz, R. et al., 2013. Analytical study and evaluation results of power optimizers for distributed power conditioning in photovoltaic arrays. Prog. Photovoltaics: Res. Appl. 21 (3), 359–373.

Oreski, G., Wallner, G.M., 2005. Aging mechanisms of polymeric films for PV encapsulation. Sol. Energy 79 (6), 612–617.

Oreski, G., Wallner, G.M., 2009. Evaluation of the aging behavior of ethylene copolymer films for solar applications under accelerated weathering conditions. Sol. Energy 83 (7), 1040–1047.

Sánchez-Friera, P., 2011. Analysis of degradation mechanisms of crystalline silicon PV modules after 12 years of operation in Southern Europe. Prog. Photovoltaics: Res. Appl. 19 (6), 658–666.

Solórzano-Moral, J. et al., 2013. A model for the simulation of energy gains when using distributed maximum power point tracking (DMPPT) in photovoltaic arrays. Prog. Photovolt: Res. Appl. http://dx.doi.org/10.1002/pip.2413.

TamizhMani, G,. 2010. Testing the reliability and safety of photovoltaic modules: failure rates and temperature effects, TÜV Rheinland.