Dust effects on PV array performance: in-field observations with non-uniform patterns

E. Lorenzo , R. Moretón and I. Luque

ABSTRACT

This paper presents the impact of non-homogeneous deposits of dust on the performance of a PV array. The observations have been made in a 2-MW PV park in the southeast region of Spain. The results are that inhomogeneous dust leads to more significant consequences than the mere short-circuit current reduction resulting from transmittance losses. In particular, when the affected PV modules are part of a string together with other cleaned (or less dusty) ones, operation voltage losses arise. These voltage losses can be several times larger than the short-circuit ones, leading to power losses that can be much larger than what measurements suggest when the PV modules are considered separately. Significant hot-spot phenomena can also arise leading to cells exhibiting temperature differences of more than 20 degrees and thus representing a threat to the PV modules' lifetime.

KEYWORDS

PV performance; dust; power losses; voltage losses; hot spots; in-field measurements

1. INTRODUCTION

Considering the effect of dust on the performance of PV modules is typically restricted to analyzing how it reduces the effective incident irradiance [1–8]. This is equivalent to assuming that dust is uniformly distributed over the PV modules and PV array surfaces, thus reducing the short-circuit current but without affecting either the open-circuit voltage or the fill factor. Thus, the power delivered is reduced in the same proportion as the distribution of the dust. However, observed dust distributions are often far from being uniform, and this non-uniformity implies some kind of mismatch between cells in the same PV module, as well as between modules within the same string. In the former case, it translates into anomalies in the *I–V* curve when the affected PV module is considered separately. In the latter, it translates into voltage losses when the affected PV module operates in a string. The corresponding power losses from the latter case can be significantly larger than what is suggested by the simple distribution of dust. Moreover, non-uniform dust patterns can also give rise to the formation of hot spots, threatening the PV modules' lifetime.

This paper presents some experimental observations made in a 2-MW PV park located at Cartagena (in the southeast of Spain). Figure 1(a) shows dust deposits on several PV modules. Strongly non-uniform patterns can be clearly observed in some of them. These patterns arise spontaneously, probably as the result of complex combinations of dominant breeze winds with the PV module frames and the arrangements of the arrays. Figure 1(b) shows dust affecting not only to the free space between the solar cells and the frames but also to some of the solar cell surface. Just to show that this case is not a very particular one, Figure 1(c and d) shows non-uniform dust patterns observed in other Spanish PV arrays. In fact, that can be often the case in non-cleaned PV arrays operating in arid regions [7,9].

Subsequent *I–V* curves and operation voltage measurements show that the derived power loss is significantly larger than the short-circuit reduction. Moreover, hot spots up to 23 degrees on the surroundings have also been observed. That is, dust deposits are acting as partial shades, but with the additional annoyance of their becoming permanent.

Figure 1. Non-uniform dust patterns spontaneously formed on PV modules and array surfaces. (a) At aforementioned Cartagena PV park, the dust shows a tendency to accumulate in the lower and on the left-hand part of several PV modules. (b) A detail of the previous figure shows that dust deposits do not only affect the free space between the solar cells and frames but also the solar cells' surface. (c) Dust on a close horizontal PV array on an industrial roof. (d) Dust on the roof of a so called "PV building".

2. IN-FIELD MEASUREMENTS

The Cartagena PV park is made up of 192-kW PV arrays, each one including 42 strings associated in parallel. Each string consists of 20 PV modules associated in series, and each PV module is made up of 60 square solar cells and three bypass diodes, arranged as Figure 2 shows. In what follows, a group of solar cells protected by a bypass diode will be referred to as a block. Measurements have been taken on the two dusty PV modules marked as M1 and M2 in Figure 1(a). The day was clear, with incident irradiances of more than 800 W/m^2 and module operation temperatures of around 50 °C. Measurements have been carried out in accordance with the subsequent steps:

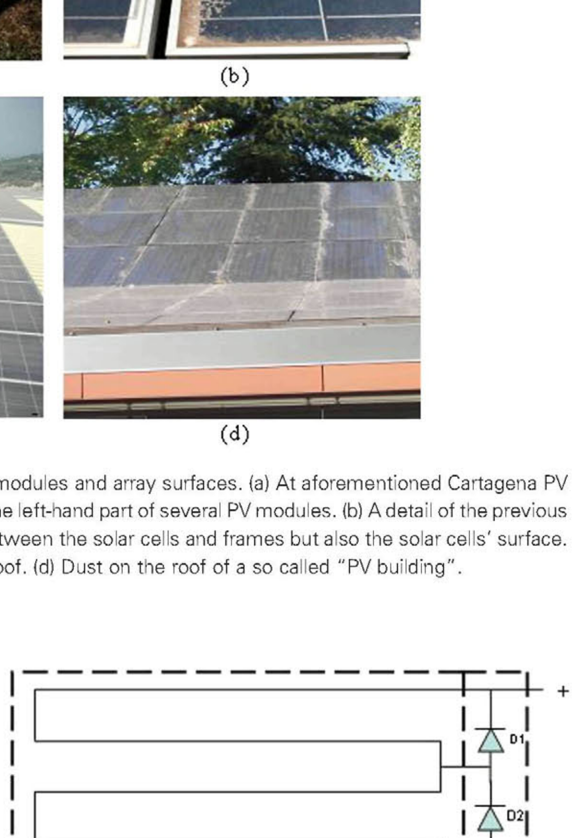

Figure 2. PV module layout.

(a) *With the inverter working and both PV modules dusty*, infrared images have been taken, showing some cells up to 23 degrees hotter than others (Figure 3). These hot spots are clearly due to dust because they disappear when the modules are cleaned. In these cells, thermal degradation must probably take place at a higher rate. It is worth mentioning that, in the lack of widely accepted norms, 20 degrees is often considered the limit for acceptance/rejection of PV modules in the current PV market. Accepting this practice would lead us to conclude that the situation observed here is not admissible and therefore, that some means of avoiding it must be adopted.

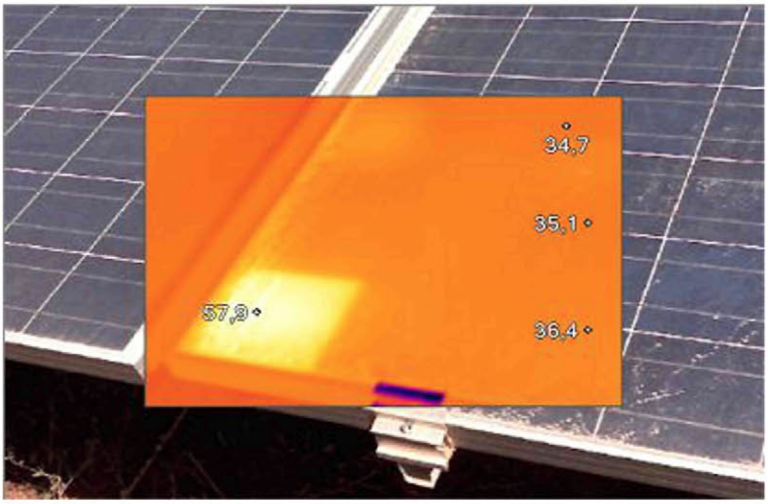

Figure 3. IR images of the lower corner of the PV module called M2 in Figure 1, showing a solar cell up to 23 degrees hotter than its surroundings.

(b) *Again, with the inverter working and both PV modules dusty*, the operation voltages of the concerned PV modules and blocks have been measured, together with those corresponding to a rather clean PV module, used as reference. This is performed by just opening the PV module connection boxes to access the intermediate contacts. The outstanding result, as Table I shows, is that, in each dusty module, the voltage of a block is significantly lower than that of the others. It is not difficult to understand that this block is just the one with the aforementioned hot cells in it, taking into account that, as a result of the dust coverage, the short-circuit current together with the maximum power current of the dustier solar cells is surely lower than those corresponding to the other cells.

Let us assume that, because the here-concerned PV modules are relatively few and dust affection is relatively low, the maximum power voltage, which is the voltage imposed by the inverter to all the strings, remains unchanged. For a first idea, let us also assume that the operation current of the affected string is roughly the same as its maximum power current.

Table I. Block operation voltage in three PV modules.

PV module	V_{D1} (V)	V_{D2} (V)	V_{D3} (V)	Total (V)
M1	9.1	9.0	4.6	22.7
M2	9.0	8.9	6.1	24.1
MR	9.0	9.1	9.1	27.2

M1 and M2 are the dusty PV modules described in Figure 1. MR is a PV module of the same string, not specifically cleaned but still been cleaner than M1 and M2, and is used as reference. Low voltage at M2-D3 and M1-D3 indicate power losses.

Hence, to allow the maximum power current of the full string to pass, imposed by the inverter, the operation voltage of this cell must be lower than that corresponding to the others, even to the extent of reaching reverse polarization, thus dissipating and not generating power. Moreover, because the current is necessarily the same throughout all the cells of the string and all of the PV modules must be roughly identical, assuming they are perfectly cleaned, power losses in the dusty PV modules are closely the same as voltage losses. In our case, voltage losses are 16.5% for module M1 and 11.4% for module M2, significantly larger than power losses when the dusty PV modules are considered separately, as is shown later on. The difference between both modules can be explained by the higher dust affection in module M1.

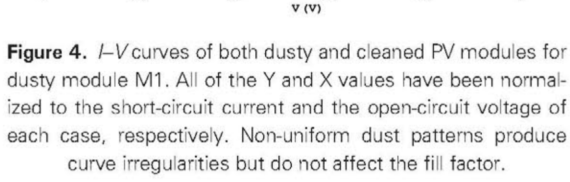

Figure 4. *I–V* curves of both dusty and cleaned PV modules for dusty module M1. All of the Y and X values have been normalized to the short-circuit current and the open-circuit voltage of each case, respectively. Non-uniform dust patterns produce curve irregularities but do not affect the fill factor.

(c) *With the inverter switched-off and both PV modules dusty*, the corresponding *I–V* curves were traced and then translated into Standard Test Conditions following the IEC-60891. Figure 4 shows the results for M1, once the Y and X values have been normalized to the short-circuit current and the open-circuit voltage, respectively. This figure also includes the *I–V* curves of the same module, but once it has been cleaned (obtained in a further step). In this way, irregularities caused by non-uniform dust patterns become evident. Figure 5 shows a close-up view of the maximum power point region. It is worth noting that the corresponding fill factor remains practically constant. This means that power reduction losses resulting from dust, when the PV modules are considered separately, are roughly the same as the short-circuit losses. However, when the dusty PV modules become part of a string together with other cleaner PV modules, these irregularities combine with the short-circuit reduction to significantly lower the operation voltage. This is shown in Figure 6, where all of the Y values (from both the dusty and from the cleaned PV module) have been normalized to the short-circuit current of the cleaned PV module, which helps to explain the previous step results. Again, Figure 7 shows a close-up view of the maximum power point region.

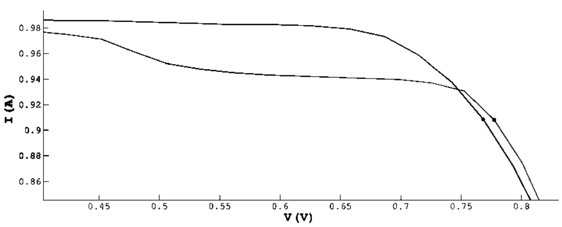

Figure 5. *I–V* curves of both dusty and cleaned PV modules for dusty module M1. Close-up view of the maximum power point region of Figure 4.

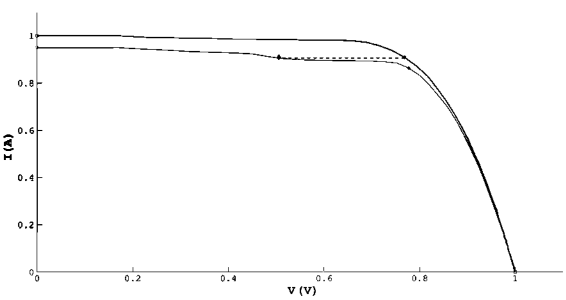

Figure 6. *I–V* curves of both dusty and cleaned PV modules for dusty module M1. All of the Y values have been normalized to the short-circuit current of the cleaned PV module. Dust causes short-circuit current losses and non-uniform patterns also cause voltage losses when both modules are forced to operate at the maximum power point current of the cleaned PV module.

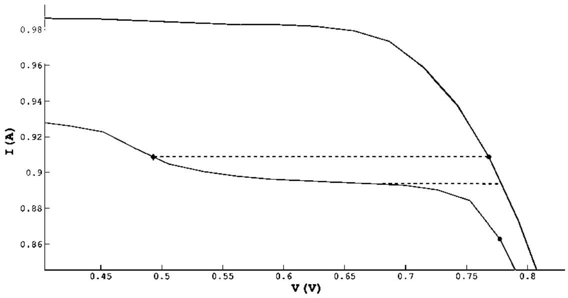

Figure 7. *I–V* curves of both dusty and cleaned PV modules for dusty module M1. Close-up view of the maximum power point region of Figure 6. Note that voltage losses at M1 depend on the operation current.

It is now opportune to note that in the case the operation current of the concerned string coincides with the maximum power current of the cleaner PV modules (as initially assumed in Section 2(b)), voltage losses at the dirty one (M1) would be 35.8%. However, just to compensate these voltage losses, voltage operation of the cleaner PV modules must be somewhat higher than its maximum power voltage. Hence, real string operation current must be slightly lower than the maximum power current, and voltage losses must also be lower than such value. In fact, experimental voltage losses are 16.5%.

(d) *With the inverter switched-off and the PV modules having been cleaned alternatively*, the short-circuit current of the two PV modules has been measured at each cleaning step. Table II presents the corresponding ratio between these currents. Because each cleaning step only affects to one PV module whereas the other remains unaffected, the variation in this ratio provides a precise indication of the short-circuit PV module losses, which is closely the same as the transmittance losses resulting from dust. Here, the resulting values are 5.5% for module M1 and 4.3% for module M2.

(e) *With the inverter switched-off and both modules cleaned*, the *I–V* curves are again traced to complete step (c) and Figures 4–7.

3. CONCLUSIONS

This paper presents a real case showing that strongly non-homogeneous deposits of dust can lead to more significant

Table II. Short-circuit current ratios throughout the cleaning sequence and losses resulting from dust.

M1 dusty/ M2 dusty	M1 cleaned/ M2 dusty	M1 cleaned/ M2 cleaned	Dirtiness in M1 (%)	Dirtiness in M2 (%)
0.985	1.042	0.997	5.5	4.3

consequences than the mere short-circuit current reduction resulting from transmittance losses. In particular, operation voltage losses arise when the affected PV modules are part of a string together with other cleaned (or less dusty) ones. These voltage losses can be several times larger than those of the short-circuit ones. In this way, the power losses of dusty PV modules in PV arrays can be larger than what measurements suggest when the PV modules are considered separately. Moreover, significant hot spot phenomena can arise leading to cells exhibiting temperatures of more than 20 degrees over those of the other cells in the same PV module, leading to a threat to the PV modules' lifetime.

We do not know how often such heavy dust deposits come about in the field, but we think that it can be often the case in PV parks operating in arid and desert areas, where cleaning is sometimes difficult because of the lack of water. Hence, we suggest paying specific attention to this problem during routine maintenance procedures. For example, by performing an IR analysis of suspicious PV array areas.

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