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Criticality of cracks in PV modules

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Abstract

The evaluation of cracks in PV modules is a difficult task: cracks do not necessarily lead to a strong degradation in the power output of the module directly after the crack initiation. However, PV modules with cracks suffer from a lower stability of the power output under artificial ageing. This is partly because cracked cell areas can become electrically disconnected from the active cell area. Here we present the analysis of the criticality of cracks formed in a uniform load test. For this we evaluate cracks which may isolate cell areas. We observe 667 cracked cells in 27 PV modules with 60 cells each. Cracks parallel to the busbars constitute 50 % of the crack orientations in our experiments. This crack orientation has a high probability of having a potentially separated cell area A_{crack} of 16 to 24 % and can thus be considered to be of high criticality. We proceed by subjecting 12 of these PV modules to 200 cycles of a humidity-freeze test. A significant part of 29 % of the cracked cells shows an increased resistance across the cracks and 7% show isolated cell areas.

Keywords: PV module reliability; cracks; uniform mechanical load; artificial ageing

1. Introduction

Cracks in PV modules are ubiquitous [1]. They may develop in different stages of the module lifetime: during manufacturing in particular the soldering induces high stresses into the solar cells [2, 3], handling and vibrations in transport can induce or expand cracks [4]. Finally, a module in the field experiences mechanical loads due to wind (pressure and vibrations) and snow (pressure).

Cracks also have the tendency to decrease the power stability of the PV-module in artificial aging [5]. In particular it was shown that the electrical disconnection of cell parts due to cracks has a large impact on the power output of a PV-module. Furthermore a field test shows that modules with cracked cells cause fluctuating power loss due to cycles of contact and isolation of the cell parts caused by thermal stress [6]. For these reasons it is imperative to reduce the vulnerability of PV modules to crack inducing mechanical loads.

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Cracks induced by a uniform mechanical load in accordance with the IEC 61215 norm test were shown to spatially distribute in a specific X-pattern [7]. It was found, that cracks parallel to the busbars constitute 50 % of the cracked cells. These cracks theoretically have the highest potentially separated cell area, leading to a maximal potential impact on the power output of the module. Up to now however the factual distribution of potentially separated cell area remains unknown. Cracks parallel to the busbars can form between the busbars, leading to no separated cell area even in the worst case. Therefore here we address the question of the criticality of cracks in PV modules by individually evaluating cracked cells after uniform mechanical load tests with respect to the potentially separated cell area. Subsequently we re-evaluate cracks after humidity-freeze tests of PV modules in order to gain information on the fraction of cracks degrading in artificial aging tests.

2. Experimental setup

In an in-house developed uniform mechanical load tester we tested 27 PV modules with 60 cells each with a two-busbar design according to the IEC 61215 mechanical load test. Before and after this test the power of the PV modules are measured by a cetis class AAA HALM flasher. We analyze the 667 cracks formed in this test with difference electroluminescence imaging [7], and classify them according to their orientation [1] with regard to the busbars, i.e. dendritic cracks, cells with several cracking directions, diagonal cracks, cracks parallel and perpendicular to the busbars. In order to analyze the criticality of the cracks, we evaluate the worst case situation for each crack. We assume that each crack would lose the electrical contact between the cracked cell parts. We manually outline the potentially separated cell area in the difference electroluminescence image. Subsequently we numerically calculate the relative cell area A_{crack} related to this crack by comparing the number of pixels on a cell with the number of pixel in an outlined potentially separated cell area. In this way we account for the factual distribution of cracks of the same orientation and analyze, if the criticality of cracks follows the theoretical worst case scenario [7].

In a next step we expose 12 of the PV modules tested in the uniform mechanical load test with 259 cracked cells to 200 humidity-freeze cycles. We measure again the PV module power and then reevaluate the cracks with respect to the impact of the aging. We discriminate between cell areas that exhibit an increase in the resistance across the crack and thus appear darker in low-current electroluminescence imaging, and cell areas that show a complete electrical separation from the active cell area, which appear black in low-current electroluminescence imaging, compare Fig. 1. We then compare the potentially separated cell area before artificial aging with the actually degraded cell area after artificial aging in order to gain an understanding of the criticality of the cracks.

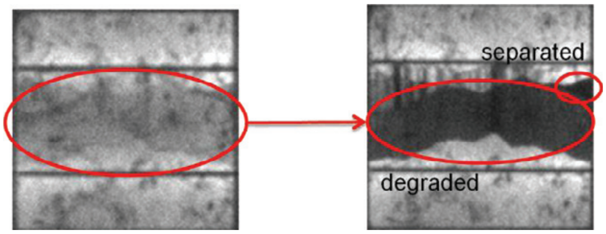

Fig. 1. Electroluminescence image at high-current conditions of a cracked cell after uniform load test (left) and after artificial aging in humidity freeze cycles (right). The central part of the cracked cell has degraded but is still connected, while a small part is electrically separated from the cell. For the differentiation between degraded and separated cell areas a low-current electroluminescence image is used.

3. Relative power loss

The relative power losses of the tested modules after the mechanical load test and the subsequent humidity-freeze testing were discussed previously [5]. A clear correlation between the number of cracks in a PV module and the relative power loss both directly after the mechanical load test and after humidity-freeze testing was found.

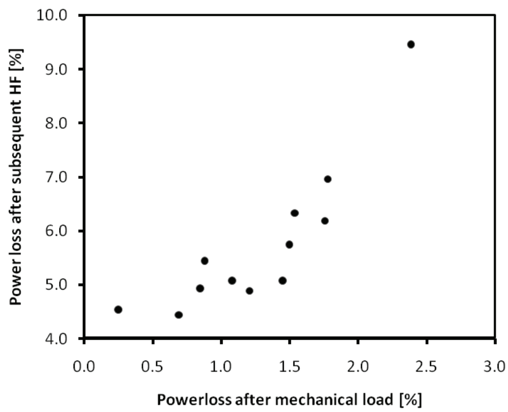

Fig. 2. Correlation between relative power losses of the tested modules after mechanical load with the power losses after subsequent artificial aging

Figure 2 depicts the power loss after the humidity-freeze cycling in dependence of the relative power loss the modules experienced directly after the mechanical load test. The correlation confirms the detrimental impact of cracks on the aging stability of the PV modules, demonstrating the need to analyze the potential impact and development of cracks in cells in more detail.

4. Crack criticality after uniform mechanical load tests

The distribution of potentially separated cell area resulting from the uniform mechanical load test of the 27 PV modules is shown in Figure 3. The different cell orientations dendritic (dark blue), several directions (light blue), diagonal (green), parallel to busbars (orange) and perpendicular to busbars (red) have substantially different distributions.

Cracks parallel to the busbars (orange) peak in the potentially separated cell area between 16 to 24 %. This corresponds very well to the discussion of the theoretical worst case scenario of 25 % separated cell area presented previously [6]. A substantial number of cracks parallel to the busbars has no risk of separating some cell area, but also worst case cell area separations of up to 52 % are present in our data set of parallel cracks. In these cases more than one crack parallel to the busbars is present within one cell.

Diagonal cracks (green) as expected have mostly much lower maximally separated cell areas. Keeping in mind that simulations have shown that a cell area loss larger than 8 % leads to relevant influence of this crack on the power output of the module [5] we find that about two thirds of diagonally cracked cells constitute no risk for the power stability of the module. Therefore we can consider diagonal cracks to be of lower criticality than cracks parallel to the busbars.

Both cells with several cracking directions and cells with dendritic cracks show a wide range of potentially separated cell areas. In particular, one single cell with dendritic cracks showed a maximally potentially separated cell area of 55 %, which is the highest value found in our experiments.

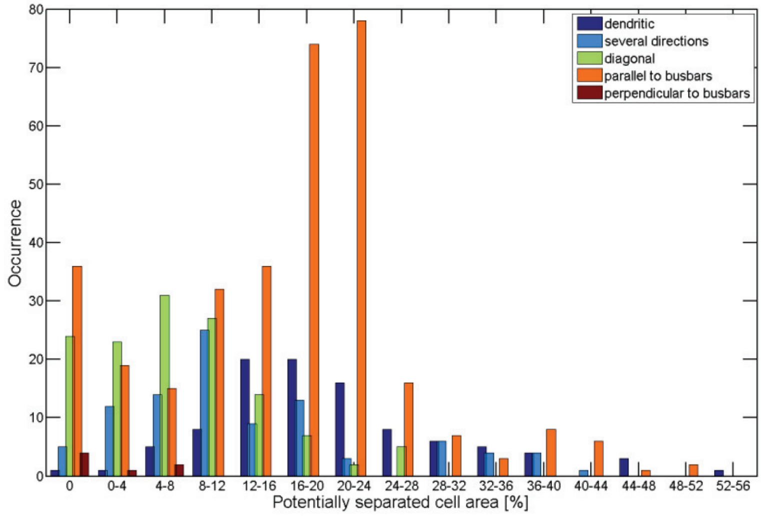

Fig. 3. Occurrence of potentially separated cell areas due to cracks with different orientations

When we combine the data for the potentially separated cell areas of all crack orientations we find that the uncritical cracks with potentially separated cell areas below 8 % amount to 30 % of the cracked cells. 70 % of the cracked cells can potentially separate a part of the cell large enough to be detrimental to the PV module power output. This means, that the majority of cracks in the tested PV modules have to be considered critical for the power stability of the module after a uniform mechanical load test representing wind and snow loads.

5. Impact of artificial aging on cracked cells

In artificial aging cracked cells can change in different magnitudes: cell areas can degrade in the sense that the resistance over the crack increases, leading to areas that appear darker in the electroluminescence than before. If the resistance over the crack is too high the cell part results being electrically isolated from the remaining cell, these areas appear black in the electroluminescence and constitute the worst case scenario.

Figure 4 correlates the potentially separated cell area with the relative cell areas that are electrically disconnected (4a) or degraded (4b). We find that of the 259 cracked cells 76 (29.3 % of the cracked cells) show an increase in contact resistance across the cracks. 19 cells (7 % of the cracked cells) exhibit electrically disconnected cell parts. Of these degraded cells only a few show a relative affected cell area of the same magnitude as the worst case estimation discussed in the previous section. This indicates that cracked cells frequently have several cracks of the same or different crack orientations, fracturing the cell area into smaller parts. On the other hand, in Fig. 4b we find that two cells show a degraded cell area although the potentially separated cell area before artificial aging is determined to be zero. These two cells both show a single non-critical crack before artificial aging in the area that is degraded afterwards. Either in these cases there is another crack undetectable with our method before artificial aging, leading to an underestimated potentially separated cell area, or an additional crack formed during the aging.

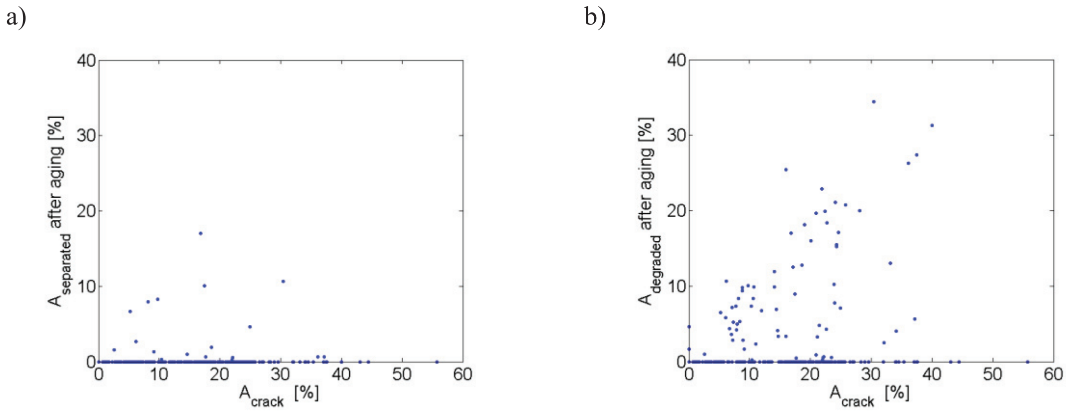

Fig. 4. Correlation between the potentially separated cell area A_{Crack} of cracked cells after the uniform mechanical load test with a) the electrically isolated area after artificial aging in humidity-freeze cycles, and b) the degraded cell area after artificial aging in humidity-freeze cycles

The magnitude of the separated cell areas depicted in Fig. 4a, which determine the impact of these cracked cells on the PV module power output, is mostly below the threshold of 8 %. Only four cells, this is 2 % of the cracked cells, have separated cell areas above the threshold, with the maximum value of 17 %.

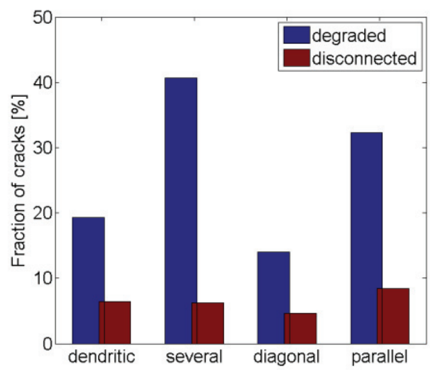

Fig. 5. Fraction of cracks of a given crack orientation that show degraded (blue) or disconnected (red) cell areas after artificial aging in humidity-freeze cycles

Figure 5 visualizes the impact of the artificial aging on cracks of different orientation. Depicted is the fraction of cracks of a given orientation that degraded and disconnected, respectively. The cracks perpendicular to the busbars are not depicted, as none of these degraded. The probability of a crack developing a disconnected cell part is in the same magnitude for all depicted crack orientations. The probability of degraded cell parts is however strongly dependent on the crack orientation: about 40 % of the cells with several crack orientations degrade, followed by cracks parallel to the busbars with 33 %. Cracks parallel to the busbars are also the most frequent crack orientation with 50 % of the cracks [7]. Keeping in mind that the potentially separated cell area of this crack orientation peaks between 16-25 %, see Fig. 3, cracks parallel to the busbars can be therefore considered of particularly high criticality for the module power output.

6. Conclusion

We analyzed the criticality of cracks formed in a uniform load test by explicitly determining the potentially separated cell area of these cracks. We observed that cracks parallel to the busbars frequently have a risk of separating cell areas of 16 to 25 %, emphasizing the necessity to particularly avoid cracks of this orientation.

After 200 humidity-freeze cycles we found that only 7 % of the cracked cells develop an electrically disconnected cell area. Also, the relative area of these separated parts is in most cases lower than the threshold for affecting the module power output. However, 29 % of the cracked cells degrade in the humidity-freeze test. Cracks parallel to the busbars and cells with several cracking directions show a high probability of degrading in artificial aging, while cracks perpendicular to the busbars did not show a degraded cell part in our tests.

The analysis presented here verifies that cracks parallel to the busbars are of particularly high criticality for the PV module power output, as they appear very frequently in uniform mechanical load tests, have high potentially separated cell areas and a high probability of degrading at least a part of the cracked area. It is imperative to manufacture mechanically stable in order to avoid the formation of cracks as much as possible.

Acknowledgements

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