Evolution of pre-cracked PV modules

Module performance | Cell cracks have been identified as a major cause of defects in PV modules, but their effect on performance is less well understood. Researchers Claudia Buerhop-Lutz, Thilo Winkler, Jens Hauch, Christian Camus and Christoph J. Brabec describe the results of ongoing investigations into how the electrical power of PV modules is impacted by cracking

High quality solar cells and modules are essential for an efficient operation and a high energy production over a 20-year lifetime or longer. During recent years there has been a large emphasis on seeking and identifying faulty and underperforming PV modules on site. Cell cracks and cell fractures have been identified as one of the major module defects [1]. The availability of mature electroluminescence (EL) imaging systems has enabled the visualisation of cell cracks and breakages [2] in PV modules. Many research projects around the world have studied the reasons for crack initiation – for example, manufacturing processes, handling, transport or installation. Nowadays, EL imaging can be carried out on site at the PV installation. That is advantageous because handling, demounting, transportation and reinstallation are avoided. Thus, on-site EL imaging directly shows the quality of installed PV modules, e. g. in terms of number of cracked cells. Therefore, it is easy to know or to determine how many modules with cracked cells are present in a solar park, for example before and after a severe storm event or a hailstorm. Consistent documentation allows for the detection of changes and identification of new faults; it states the current situation. However, it is still unknown what the identified faults mean for future performance.

The interesting questions are, firstly, how do these cracked and pre-cracked modules perform, what is the remaining/residual power output, and, secondly, how will these pre-cracked PV modules perform under operating conditions with temperature cycles, wind and snow loads in the future.

In order to study the performance before and after a special event, we designed a special setup [3], so that we could monitor the changes with an EL camera directly and if necessary in real time. In order to sensitise the PV community to the stresses induced in PV modules by mechanical loading, we mimicked the manual cleaning process. This is of importance because locally severe loads occur when persons walk across the modules. For the experiment we used a pre-cracked, polycrystalline PV module (module with existing cracked cells) which was approximately two years in operation. Figure 1 illustrates the change of the EL image of the pre-cracked module before, during and after the manual cleaning process. The left image shows the initial EL image of the module, 10 cells in total have cracks. Of these, five already exhibit open cracks, recognisable by the grey areas. The centre image illustrates the situation when somebody sets foot on the module. The changes are clearly visible (see also [4]). The previously grey cell areas turn black, more cells show open, grey areas, and further cracks are initiated in previously good cells. According to the local stress distribution in the module, mainly cells in the centre fail. After walking across the module, what remains are 19 cracked cells, eight with open cracks (see right image in Figure 1). The resulting electrical performance reveals that the measured power using a sun simulator varied about 1%, which is within the measurement accuracy.

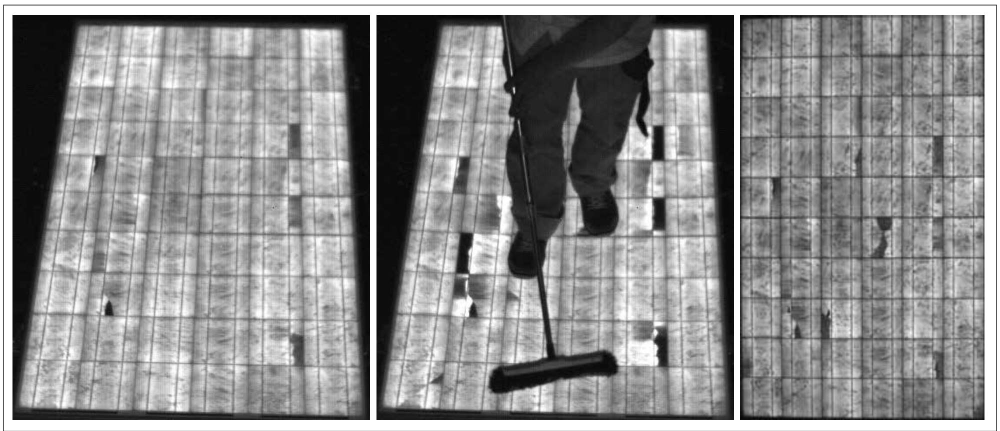

Figure 1. EL-image of pre-cracked PV-module, left: before stepping on the module, middle: while setting foot on the module e.g. for manual cleaning, right: after walking on the module [6]

These results give a first insight into the importance of interpretation of EL images. High loads can cause cracks and fractures which look dramatically deteriorated in the EL-image because of their fairly black appearance. However, unloading the module, the cracks remain but they close. The pattern of cells with grey, fractured cells changes as well as the EL-intensity distribution (dark areas are less dark). Open cracks (recognised by a darker, grey to black cell part) can influence the power output according to their remaining electric contact with the main, current-conducting cell parts. Cells with open cracks can be a risk for power reduction [5]. Closed cracks do not impact the power output. The direct correlation between EL image and module power highlight that a quick, superficial view at an EL image of a module with broken cells shows the mechanical condition of the module, whereas it is not sufficient to deduce the power output.

Mechanical load testing

Answering the question, how this module may perform under real outdoor operating conditions, an accelerated mechanical load test mimicking the weather conditions at a fictitious site of interest was carried out.

A new test facility was designed and built to simulate mechanical loads and give insights into crack initiation and growth in solar cells. The newly developed mechanical load test setup applies uniform homogeneous pressure to the module by applying under-pressure from the backside of the module. The pressure is controlled and varied by gauges. Simultaneously, the IV-curves, respectively the module power at maximum power point, and EL images are recorded. Changes in the crack structures are detected and correlated directly with electrical data [3, 7]. In comparison to standardised tests [8], which consider temperature and humidity cycles, we focus on mechanical loading in order to mimic realistic wind and snow loads during operating.

For the test scenario we consider a fictitious PV system installed in Central Europe with moderate continental climate. The ambient temperature reaches from -20°C in winter up to 35°C in summer. Therefore, the PV modules are exposed to daily temperature differences of up to 65K. Especially on hot summer days and clear nights, high module temperatures in the daytime and fairly low temperatures at nighttime occur. Snow heights of relevant static pressure causing cracks were neglected. However, wind gusts were studied. As a first approach, we analysed the distribution of the maximum daily wind speed over one year. At the fictitious PV site, e. g. in Bavaria in Germany, there were two hurricane events (v > 120km/h), several stormy days (90km/h < v < 120km/h), many windy days (50km/h < v < 90km/h) within the year. On most days the maximum wind speed was more or less a gentle breeze (v = 24km/h). According to the standard DIN 1179, "Eurocode 1: Actions on structures - Part 1-4: General actions - wind loads, 2010", the resulting pressure on the modules was calculated. The wind pressure distribution reveals that up to 90% of the wind loads are less than p = 200Pa (corresponding to v = 56km/h), 5% between 200Pa and 400Pa (corresponding to v = 80km/h), and rarely p = 1,000Pa (corresponding to v = 120km/h), and p = 1,200Pa (corresponding to v = 140km/h). For simplifying the experimental procedure we grouped the identical cycles between same load levels (e. g. 200Pa to 0 Pa, or 1,000Pa to 0 Pa (which simulates the unloaded, normal state)). Low load cycles were carried out much more often within one run than high load cycles. High load runs (Δp > 200Pa) were always followed by a low load run (Δp = 200 Pa). At the end of the cycling test procedure 22,360 cycles or 34 runs were applied to the module (see Figure 3). In more detail, throughout the test procedure almost 20,000 times low load cycles were done, 250 times high load cycles (Δp = 1,000Pa) as well as 10 times very high load cycles (Δp = 1,500 Pa). After each run EL-images as well as power measurements were recorded.

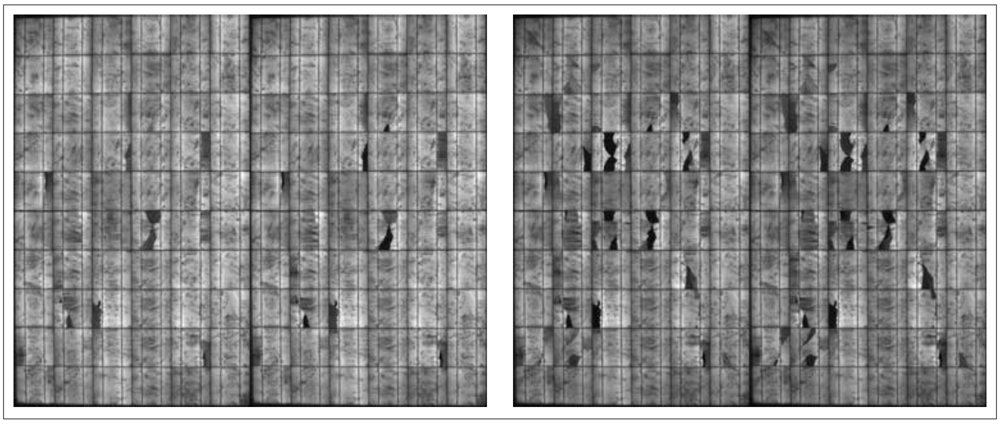

Figure 2. Sequence of EL images of PV module undergoing mechanical loading with an increasing number of cycles and extra heavy loading (p = 5,000Pa) at run 28, from left to right: run 0 (initial stage), run 27 (before heavy loading), run 29 (after heavy loading), run 34 (end of cycle)

Figure 2 shows the EL images of the "manually" cleaned PV module, on which somebody set foot, before and after simulating alternating wind loads in the lab. The images are always recorded at the unloaded state. The test cycle is divided in two phases, first, before high loading with 5,000 Pa, second, after high loading.

Through the first 16,000 cycles (Figure 2, run 27) no significant changes took place, the EL-image shows the same 19 cells with open and closed cracks. Just the intensity distribution modified a little. Surprisingly, cell fragments of broken cells in the centre show a better electrical connection, lighter in the EL image, than at the beginning. Obvious changes due to heavy loading in run 28 are exhibited in the EL image of run 29. The load of 5,000 Pa was so high that 12 previously good cells, especially in the corner and the centre, show new cracks. An increased number of cracked cells with grey to dark cell areas is visible. Throughout the following 6,000 cycles until the end no further obvious changes can be detected in the EL image. The number of cells with open and closed cracks remains constant.

The findings in the EL images are reflected in the power data. The relative power output drops from 99.8% to 99.4% through the first part of the cycle test. The power reduction is rather small since only two cells with extremely black areas are present in the module. They potentially impact the module's electric performance. The other grey-black cell fragments are of minor importance. Then, due to the high loading a power drop of roughly 1% is measured: 31 cells are cracked, 12 cells with pitch-black areas cause the reduction. Continuing the cycling test, the power loss is in the range of 1.1%. No changes in the cell structure are detectable. Thus, a total power reduction of 2.5% results (see Figure 3).

The judgement of experience points out that the performance between moderate, uniform loads on PV modules and exceptional loads differ. There is a creeping power loss between 0.8% and 1.4% for other modules tested with the same procedure except the extra high loading. On the other hand a spontaneous power loss of roughly 1% was measured for extra high loading events. The power does not decrease continuously, as shown in Figure 3. It rather alternates. This may be explained by the quality of the electric contact of the crack faces and respectively the cell fragments. In accordance with the power fluctuation the appearance of the EL image changes. Electrically unconnected cell fragments are black in EL because they do not emit luminescence. The better the fragments are electrically connected, the lighter they appear. During the loading and unloading cycles the fragments might be moved and shifted a little bit. That can have a significant impact on the electric contact and accordingly on the power output. Thus, careful evaluation and comparison of EL images and electrical data of modules with cracked cells is recommended. The rearrangement of cell fragments does not only happen during cycling, it is also is possible during other procedures, e.g. handling, installation or transport.

For relating the cycling test to a time period at real operating conditions, as a first guess, 10 to 20 wind gusts in average per day are estimated. Then, 22,360 cycles equal roughly 3-6 years. A worst case scenario potentially yields 1.4% degradation of pre-cracked PV-modules in three years. Published field studies of the performance of pre-cracked PV modules at real operating conditions present similar data [9, 10]. However, the investigation periods of field exposure are still rather short and the measured power changes over time are within the measurement accuracy for field measured IV-curves.

In summary, the investigated pre-cracked polycrystalline PV modules seem to degrade rather benignly at mimicked wind loads at moderate European climate for the first years. For more reliable long-term conclusions, more scenarios have to be studied for longer periods of time. The appearance of the EL images changes, cracks open and close, the electrical contact of the crack faces varies during the cycling test. New cracks in good cells occur quite rarely at moderate weather conditions. In contrast, high and local loads may cause cell breakage and be a risk for spontaneous power reduction. The power loss of modules with cracked cells is estimated of about 0.5% per year for moderate weather conditions.

In order to deepen the understanding of the degradation and performance of good and pre-cracked modules at real operating conditions, the study will be intensified in the future. The focus will be on testing modules of different technologies, analysing PV sites where the modules are exposed to higher stresses, and studying different failure modes, e. g. hail damage. Cooperation with interested parties is very welcome and essential for further progress.

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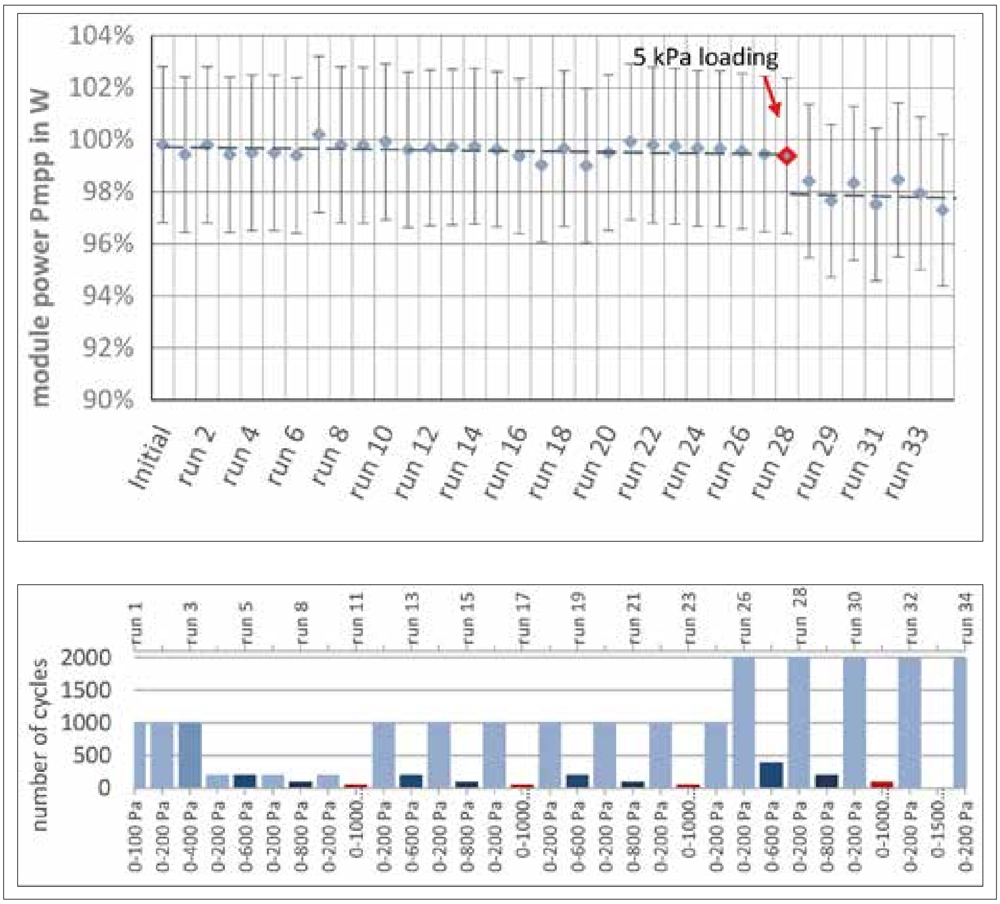

Figure 3: Cycling test, top: measured module power after cycling test with pressure p = 200 Pa simulating wind speeds of v_{wind} = 56 m/s, bottom: cycling procedure of the 34 runs

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