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EXAMINATION OF PV SILICON MODULE DEGRADATION UNDER HIGH VOLTAGE BIAS AND DAMP HEAT BY ELECTROLUMINESCENCE

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ABSTRACT: The photovoltaic (PV) modules are in PV arrays normally connected in series and thus some of them exposed to high system voltages since frames of the PV modules are grounded. To predict the long-term PV system energy output and PV module lifetime, it is very important to understand and take into account the degradation process of PV modules under high voltage stress. Accelerated tests under damp heat (over 1300 hours of DH85/60; RH = 85 %, T = 60 °C) of in-house developed monocrystalline silicon PV modules were performed while connected to a positive or negative voltage bias of 1000 V. The negative biased modules exhibited just a little degradation, while the positive biased modules degraded rapidly. We identified three degradation mechanisms: ion migration, silver corrosion and EVA evaporation. The degradation mechanisms contribute to almost 15 % of the performance loss of the 1000 V positive biased modules after more than 1300 h of DH85/60 testing, while the power degradation of the negative biased modules remains below 3 %.

Keywords: high voltage stress, PID, leakage current, PV modules, degradation

1 Introduction

In the last decade, photovoltaics (PV) became an important renewable energy source. Many large PV power plants up to several hundred MW are already in operation. To reduce the joule losses in the DC power lines of the PV generator it is favourable to increase the system DC voltage, therefore multiple PV modules are connected in series. Currently, the PV system voltages are up to 600 V (USA) or 1000 V (EU). Additionally, there are discussions to go even further to a 1500 V system voltage in large PV power plans. Thus, PV modules in the strings are exposed to high voltage bias stress. The modules have to withstand the voltage stress between the solar cells and the grounded aluminium frame that gives PV modules mechanical strength. High voltage bias stress can influence the degradation of a PV module by a potential induced degradation (PID) [1]. The PID is caused by ion migration between solar cells and other materials like glass or aluminium frame in a PV module that is grounded. Intensity of the process is determined by the system voltage and depends on the PV module potential, defined as the voltage between the connectors or active cell area and grounded module frame. The potential depends on the system electrical configuration. If the string is not grounded on any side, the modules are between the half of the negative system voltage and the half of the positive system voltage. If one end of the string is grounded, the modules are on potentials up to the system voltage in the negative or positive polarity. Furthermore, investigations have shown that ion mobility and corrosion effects are temperature and humidity dependent. Increase of the potential, temperature or humidity accelerates the degradation mechanism [2].

The PID effect was first discovered in the 1970's [2] but it started to be largely investigated in the last decade after the investigation of the SunPowers' polarization effect [3]. Several studies of the PID and leakage current under high voltage stress (e.g. [4]–[7]) have been published. They investigate the evolution of the PID during accelerated testing and also in field operation. Most of the published studies deal with the PID effects only on modules with negative bias polarity [1], [5], [6]. The influence of the positive high voltage stress on the PV module is rarely described in the literature [8], [9].

PID in crystalline silicon PV modules with *np*-type solar cells causes “surface polarisation” [2] and is therefore reversible. However, if high voltage bias stress influences corrosion the process is irreversible. Some solutions how to avoid PID have been already reported on the cell and module level and also on PV system level [1]. Some inverter manufacturers already offer a reverse bias of PV strings during the night time to heal the short-term reversible PID influence and prevent the long-term one [10].

In this paper, we are presenting an investigation of leakage current behaviour during accelerated damp-heat testing supported by electroluminescence (EL). The influence of both, positive and negative, high voltage bias polarities on performance have been tested and results critically evaluated.

2 Methodology

To investigate the influence of the leakage current in PV modules under high voltage bias stress we developed seven small area crystalline silicon PV modules with dimension of 23 x 33 cm². The modules are denoted as Module#_xy, where # is the number of the module, xx the testing condition (DH – damp heat or RC – room condition) and y the voltage polarity (+, – or o). The module fabrication procedure followed a typical commercial manufacturing process, only on a small size and manually assembled. Each module consists of 12 small-area solar cells connected in series. The solar cells with a dimension of 78 x 39 mm² were cut out from high efficient p-type monocrystalline silicon solar cells by a laser cutter (Trotec Speedy 300). The laser cuts the cells up to the half of the total depth; afterwards the cells are broken apart. Due to the small dimension of the module, we used a thinner aluminium frame to seal them and a smaller junction box usually used in thin film technologies. For the front module’s surface, we used a commercially available textured solar white glass (Saint-Gobain Albarino), the EVA foil from NovoPolymers and the backsheet from Coveme.

Before the test, we characterized all PV modules electrically to obtain the initial STC parameters and investigated them by the electroluminescence imaging technique. For the experiment, four modules were exposed to accelerated test conditions DH85/60 in a climate chamber (Kambič KK2310-CHLT) with relative humidity (RH) and temperature of 85 % and 60 °C, respectively. The climate conditions were chosen with regard to the defined PID test requirements in the IEC-62804 standard [11]. During the test, the high positive or negative voltage bias was applied between the module connections in short circuit and the grounded frame. Two additional modules were tested at room climate conditions (RC) and were positive or negative biased. The last module was kept unbiased in the dark as a reference. The leakage current of each individual module was measured every 10 seconds with a datalogger [12].

During the test two modules exposed to the damp heat test (DH85/60) (one positive and one negative biased) and both modules tested under the room conditions (RC) were periodically characterized for performance. The other two modules in the chamber were kept in the chamber to prevent the climatic shocks throughout the whole experiment. The test period was over 1300 h, way longer than the PID test (96 h) and damp heat test (1000 h) as required in the qualification standards IEC-62802 [11] and IEC 61215 [13], respectively.

The initial rated power under STC of the tested PV modules together with the test conditions are presented in Table 1. All small area modules exhibit similar initial power output except for module Module2_DH+ in which an unconnected part of the cell (discovered by electroluminescence) lowers the module’s performance.

Table 1: Initial STC parameters of the modules under test.

modul	P_{src} (W)	η (%)	I_{sc} (A)	V_{oc} (V)	FF (%)	test condition	bias (V)
Module1_DH+	7.27	9.65	1.28	7.29	78.0	DH85/60	+1000
Module2_DH+	6.91	9.18	1.27	7.33	74.1	DH85/60	+1000
Module3_DH-	7.32	9.71	1.29	7.33	77.3	DH85/60	-1000
Module4_DH-	7.31	9.70	1.29	7.32	77.5	DH85/60	-1000
Module5_RC+	7.27	9.66	1.27	7.32	78.1	RC	+1000
Module6_RC-	7.18	9.52	1.28	7.24	77.5	RC	-1000
Module7_RCo	7.13	9.47	1.28	7.25	76.8	RC	open circuit

Figure 1: Electroluminescence pictures of the tested modules before the test (room temperature and $I = I_{sc_STC}$).

From the electroluminescence images (Figure 1) we can see some inhomogeneities, which arise during the manual module assembly procedure. The majority of them are micro cracks and contact finger interruptions, which we assume to occur due to the manual soldering procedure and due to breaking of the solar cell after laser cutting.

3 Results and discussion

3.1 Leakage current

The leakage current between short-circuited connections and the ground was monitored throughout the whole experiment in a 10 second measurement interval. The leakage current of modules tested at the room conditions was too small (in range of nA) to be measured. Modules under DH85/60 test exhibit a leakage current that changes over time. A short-term change occurred each time the climate

chamber door was opened, since the humidity dropped rapidly, but regardless to the change, the leakage current converges to the long-term expected value. Depending on the applied bias voltage, the long-term leakage current change has a shape of a negative exponential growth or exponential decay. Additionally, at positive bias we could observe a magnitude higher leakage current values than at negative bias. The phenomena was already observed in some tests [8], [14], but the magnitude of the difference in our test is much higher. Following the literature [15] the current is linked to the ease of the electrode ionisation. At positive bias, the silver anode gives a higher current than the aluminium frame anode at negative bias.

The leakage current of positive biased modules was rising over the time to a “saturated” value (negative exponential growth) and start to decrease when the degradation mechanisms became noticeable. The leakage current at negative biased modules was decreasing (exponential decay) over time to a more or less stable value. The current stabilizes when the EVA in the front and at the back of the cell is completely water soaked [16]. The leakage current of all four modules is presented in Figure 2. The spikes in the plot occur due to and at the opening of the chamber for module characterization measurements.

Figure 2: Leakage current of high voltage biased PV modules in a climatic chamber under DH85/60 over the time.

3.2 Power output and electroluminescence

The STC power output of all modules is presented in Figure 3, and shows that the positive biased modules start to degrade very early. The module Module2_DH+ exhibits almost a linear degradation rate. The module Module1_DH+, which was kept in the chamber during the test to prevent climatic shocks and was measured first after 1150 h of DH85/60 test, confirms the degradation behaviour. The negative biased modules (Module 3_DH- and Module4_DH-) do not show any degradation mechanisms during the test up to 1100 h. After 1100 h, the modules start to degrade slowly. Following the results, the modules do not indicate any predispositions to PID effects when negatively biased. Modules under RC do not show any changes in STC power nor EL after the test.

Figure 3: Normalised output power output of tested modules.

In Figure 4 the I - V curves of a positive (Module1_DH+) and a negative (Module4_DH-) biased module in DH test are presented. Positive biased module shows degradation in series resistance, V_{oc} and short-circuit current. Negative biased module do not show a large degradation in current-voltage characteristics. A small increase of the series resistance was observed at latest measurements only.

Figure 4: I - V characteristics of positive (Module1_DH+) and negative (Module4_DH-) biased module in DH85/60 under conditions close to STC.

The source of the degradation mechanisms was investigated by the EL technique. The EL inspection was done initially (Figure 1) and again after 1150 hours of DH85/60 test when all the modules were taken out from the climate chamber for characterisation. The EL images of one positive and one negative voltage biased module together with their initial EL images are presented in Figure 5. The degradation locations can be easily visualised by comparison of EL images before and after the DH85/60 test.

Figure 5: Electroluminescence images of positive and negative voltage biased modules before and after 1150 hours of the DH85/60 test.

Table 2: Average EL intensity and output power values before and after the 1150 hours of DH85/60 test, normalized to the reference module.

	initially		after the test		after vs. initial ratio	
	normalized Φ_{EL}	normalized P_{STC} (W)	normalized Φ_{EL}	normalized P_{STC} (W)	Φ_{EL}	P_{STC}
Module1_DH+	1.037	1.019	0.528	0.860	50.9%	84.5%
Module2_DH+	1.034	0.966	0.553	0.837	53.5%	86.6%
Module3_DH-	1.051	1.012	0.959	0.983	91.2%	97.1%
Module4_DH-	1.057	1.007	0.920	0.980	87.1%	97.4%
Module5_RC+	1.028	1.008	0.975	1.008	94.8%	99.9%
Module6_RC-	1.046	1.011	0.996	1.012	95.2%	100.1%

Module7_RCo	1.000	1.000	1.000	1.000	100.0%	100.0%
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Table 2 shows normalised average EL intensity values together with the normalised maximum power output values of all tested PV modules before and after the 1150 hours of DH85/60 test. The values are normalized to the EL and P values of the Module7_RCo reference module. The negative biased modules exhibit a small degradation ($< 3\%$) of the STC module power, while the EL response is lower for around 10 %. Visually, the solar cell starts to change/degrade from the edges closely to the grounded aluminium frame. These cell edges are more sensible to the ion migration due to the short distance between the cell surface and the frame. The degradation is clearly visible on the second and third cell from the module's top (in the portrait orientation) on the right hand side of the Module4_DH-module (Figure 5). Since the output power degradation of the negative biased modules after 1150 h of DH85/60 test is below 5 %, the modules can be classified as PID resistant for negative voltage bias stress.

The degradation of the positive biased modules is clearly visible from the EL images with areas of much lower EL intensities. The degradation mechanism differs from the one on negative biased modules. Following the EL and visual inspection of the modules, we could determine three different degradation phenomena: cell degradation, EVA evaporation and colorization/corrosion of the silver conduction lines (busbars/fingers).

The solar cell degradation is more pronounced at the top and bottom cells (in portrait orientation). While inspecting the sole solar cell, the highest degradation (determined from the EL response) can be seen in the centre of each cell. More precise, the degradation is larger in the centre of the active part of the cell (between the bus bar and the edge of the cell). According to the results by Liu [17], the cell degradation occurs due to the migration of Na^+ ions. In total, the power output of positive biased modules was reduced by around 15 %, while the EL intensity was reduced for almost 50 % (Table 2).

The conduction lines of both positive biased modules have completely corroded after 1150 hours of DH85/60 test. With a positive bias, the ionisation of the silver with the reaction of $\text{Ag} \rightarrow \text{Ag}^+ + \text{e}^-$ is stimulated and accelerated. High corrosion of silver contact lines results in higher series resistance of the module (see I - V curves in Figure 4). Additionally, above the metal bus bar and metal finger the EVA foil starts to evaporate. The small acetic acid bubbles [18] can be seen from the macro images in Figure 6. The bubbles are trapped in the pyramidal shaped rear surface of the front glass.

Figure 6: Macro photos of the positive biased Module2_DH+ after 1150 h (a - corroded fingers, b - busbar area on the cell, c – zoomed in photo of bubbles on a busbar from b)

To prove the silver corrosion we made an additional test of small samples of silver laminated in the same way as a PV module, just without solar cells. The silver was connected to the positive or negative potential while the glass of the sample was covered with a grounded copper foil. After less than 100 hours under DH85/60 conditions in the climate chamber the silver that was connected to the positive voltage bias of 1000 V begun to colorize, while no change could be observed in the negative biased

sample. In Figure 7 both samples after the test are presented. The experiment proves the corrosion of silver under high positive voltage bias in a high temperature and humid environment.

Figure 7: Macro photos of the positive (left) and negative (right) biased silver laminated in EVA between glass and backsheet after less than 100 hours of the DH85/60 test.

4 Conclusion

We investigated how in-house developed monocrystalline silicon PV modules behave at high voltage bias stress under room and damp heat DH85/60 conditions. The modules were exposed to 1000 V positive or negative bias. Degradation mechanisms of PV modules under high voltage stress differ with regard to the bias polarity. At the negative biased modules, we could not observe any potential induced degradation within 1000 h of DH85/60 test. The modules start to degrade slowly after 1100 h of the test. The degradation of the active layer of the cell started from the cell edges closest to the grounded aluminium frame of the module. After more than 1150 h of DH test the modules power was only around 2 % lower than before the test. On the contrary, the positive biased modules start to degrade very early, already after 200 h of DH85/60 test, which is only double than the recommended PID test duration in the qualification standard (96 h). The positive biased modules degrade due to conduction lines corrosion, ion migration (cell degradation) and evaporation of the EVA foil. The degradation started with the ion migration while the corrosion became visible after around 1000 h of the DH test. The total degradation rate was linear. After 1150 h of the DH test the PV module output power drops for 12-15 % with regard to the initial value. No degradation and also no measurable leakage current was observed for modules at room conditions under voltage bias.

The high voltage bias stress in modules can lead to a rapid and substantial performance drop of PV modules. Even if modules are not sensitive to the PID at a negative bias, they can degrade at a positive voltage bias stress. Especially in warm and very humid environments. For these modules, the solution to invert the PV system voltage during the night may be a good countermeasure to prevent or at least mitigate the degradation.

In our experimental study, we observed that the degradation of a positive high voltage biased PV module in a very humid environment could be more severe than if the module is negative voltage biased. Since our test conditions were steady-state the degradation mechanisms under dynamic real-time conditions may be less evident. Anyhow, most of the research in the field of PID has been focusing on the negative biased modules where common degradation effects appear. However, PID is not only temperature and humidity dependent but is largely affected by the materials used in the PV module. With our experiment, we could prove that the silver corrosion in some cases could be even more detrimental than the “standard” negative potential induced degradation. Additionally, the negative PID effects are in some ways reversible by inverting the PV system voltage during the night, while the silver corrosion at positive biased modules is irreversible. Thus, a PV system with negative biased PV modules is more preferable and less sensitive to the potential induced degradation mechanisms in general.

5 References

- [1] S. Pingel, O. Frank, M. Winkler, S. Daryan, T. Geipel, H. Hoehne, and J. Berghold, "Potential Induced Degradation of solar cells and panels," Proc. of 35th IEEE Photovoltaic Specialists Conference (PVSC), 2010, pp. 2817-2822.
- [2] Anvanced Energy, "*Understanding Potential Induced Degradation*" [Online]. Available: http://solarenergy.advanced-energy.com/upload/File/White_Papers/ENG-PID-270-01%20web.pdf. [Accessed: 17-Aug-2016].
- [3] R. Swanson, M. Cudzinovic, D. DeCeuster, V. Desai, J. Jürgens, N. Kaminar, W. Mulligan, L. R. Barbarosa, D. Rose, D. Smith, and others, "The surface polarization effect in high-efficiency silicon solar cells," Proc. of 15th International Photovoltaic Science & Engineering Conference, 2005.
- [4] J. A. del Cueto and T. J. McMahon, "*Analysis of leakage currents in photovoltaic modules under high-voltage bias in the field*," Progress of Photovoltaics, vol. 10, no. 1, 2002, pp. 15-28.
- [5] H.-C. Liu, C.-T. Huang, W.-K. Lee, and M.-H. Lin, "High Voltage Stress Impact on P Type Crystalline Silicon PV Module," Energy Power Engineering, vol. 05, no. 07, 2013.
- [6] N. G. Dhere, N. S. Shiradkar, and E. Schneller, "*Evolution of Leakage Current Paths in MC-Si PV Modules From Leading Manufacturers Undergoing High-Voltage Bias Testing*", IEEE Journal of Photovoltaics, vol. 4, no. 2, 2014, pp. 654-658.
- [7] J. A. Del Cueto and S. R. Rummel, "*Degradation of photovoltaic modules under high voltage stress in the field*", SPIE Solar Energy and Technology, 2010, pp. 77730J-1-77730J-11.
- [8] P. Hacke and S. E. C. Nederland, "*Characterization of multicrystalline silicon modules with system bias voltage applied in damp heat*", Proc. of 25th European Photovoltaic Solar Energy Conference and Exhibition, 2011, pp. 244-250.
- [9] Z. Xiong, T. M. Walsh, and A. G. Aberle, "*PV module durability testing under high voltage biased damp heat conditions*", Energy Procedia, vol. 8, 2011, pp. 384-389.
- [10] SMA, "PV Offset Box." [Online]. Available: <http://files.sma.de/dl/15437/PVOFFSETBOX-DEN1444-V10web.pdf>. [Accessed: 17-Aug-2016].
- [11] IEC Standard, "System voltage durability qualification test for crystalline silicon modules", IEC-62804.
- [12] "LPVO: Datalogger." [Online]. Available: <http://lpvo.fe.uni-lj.si/en/services/prototype-development/datalogger/>. [Accessed: 17-Aug-2016].
- [13] IEC Standard, "*Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval*", IEC-61215 Ed2.
- [14] G. R. Mon and R. G. Ross, "*Electrochemical degradation of amorphous-silicon photovoltaic modules*", Proc. of 18th IEEE Photovoltaic Specialists Conference, 1985.
- [15] G. R. Mon, L. Wen, R. G. Ross, and D. Adent, "*Effects of temperature and moisture on module leakage currents*", Proc. of 18th IEEE Photovoltaic Specialists Conference, 1985, pp. 1179-1185.
- [16] M. Jankovec, F. Galliano, E. Annigoni, H. Y. Li, F. Sculati-Meillaud, L. E. Perret-Aebi, C. Ballif, and M. Topič, "In-Situ Monitoring of Moisture Ingress in PV Modules Using Digital Humidity Sensors", IEEE Journal of Photovoltaics, DOI: 10.1109/JPHOTOV.2016.2583779, 2016.
- [17] H. C. Liu, C. T. Huang, and W. K. Lee, "Study of potential induced degradation mechanism in commercial PV module", Proc of 38th IEEE Photovoltaic Specialists Conference (PVSC), 2012, pp. 455-458.
- [18] M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, "Potential Problems with Ethylene-Vinyl Acetate for Photovoltaic Packaging", Journal of Electrochemical Society, vol. 136, no. 4, 1989, pp. 204-212.