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Investigation of leakage currents depending on the mounting situation in accordance to amorphous silicon modules

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Abstract

System induced degradation can occur depending on the system design of PV power plants. In case of amorphous silicon solar modules this causes e.g. a diffusion of sodium ions from the cover glass into the TCO front contact, followed by a chemical reaction that leads to an irreversible power loss and is called TCO-corrosion. Leakage currents between the cover glass and the electrical connectors can be used as an indicator of the corrosion rate.

It is state-of-the-art that a negative potential of the TCO-layer in respect to the cover class (resp. mounting structure) can have an impact on the corrosion process. To avoid corrosion the negative DC pole of the PV-generator has to be grounded. Thus a positive potential occurs between the TCO-layer and the cover glass and the positive charged sodium ions do not migrate into the TCO-layer [2]. In contrast to this, the results of newer studies show that the corrosion occurs for positive potentials, too [3, 4]. Consequently the basic objective of this paper is the analysis of leakage currents according to the mounting and grounding situation of amorphous silicon solar modules under outdoor conditions. For this purpose nine amorphous silicon solar modules were mounted with different mounting systems, with backrails and module clamps. Furthermore, an external voltage with negative and positive bias is applied between the mounting system and the short-circuited module connectors. Additionally the influence of an AC potential is investigated. This case may occur due to perturbations of an inverter. The leakage currents were measured and logged continuously.

Keywords: system induced degradation, TCO corrosion, leakage current, aSi:H

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1. Introduction

Thin film solar modules (TFSM) promise a high cost reduction potential. These types of modules are made of highly absorbent materials. Therefore, the cell thickness can be reduced to less than 1µm, whereas crystalline silicon (cSi) solar cells need 100 to 200 times thicker cells. In contrast to crystalline solar modules the cells were deposited from the gas phase. This fully automated production process requires significantly less energy, which leads to comparatively shorter energy payback times. The low production costs are followed by lower module efficiencies. So, more area is necessary to achieve the same installed power like a crystalline photovoltaic power plant. For that reason, the cost advantage is especially beneficial for large scale mounted photovoltaic (PV) systems.
In order to reduce ohmic losses, the system voltage amounts often up to 1000 volts DC. It is also regularly discussed by experts to increase the system voltage up to 1500 volts DC. This heightening promises a further reduction of ohmic losses. On the other hand high system voltages can lead to a power degradation of the PV modules. In case of amorphous silicon (aSi:H) and cadmium telluride (CdTe) solar modules a diffusion of sodium ions out of the front glass can occur, if the layer deposition starts at the cover glass. In this context, if the deposition of the single layer starts from the front glass the module is a so called superstrate module. If the deposition starts from the back side cover it is a substrate module. This diffusion causes electrochemical reactions in the TCO layer of the module and leads to the so called TCO-corrosion [1]. These reactions are followed by irreversible power degradation. The rate of the diffusion depends on three main factors [2]:

- moisture infiltration,
- type of glass (existence of sodium ions) and module (superstrate design),
- potential between module and ground.

The rate of diffusion can be visualized by leakage currents. For that purpose, the leakage currents have to be measured between module and ground.

The resulting potential between module and ground is essentially determined by the type of inverter. To dictate a particular potential, the PV generator must be grounded. A grounded negative pole leads to a positive potential between module and ground. This promises a prevention of the diffusion of positive charged sodium ions (Na^+) from the cover glass to the TCO layer. However, grounding is only possible if there is a galvanic separation between inverter input (DC) and inverter output (AC). This fact requires an inverter with transformer. This is followed by higher power losses compared to transformerless inverters.

The mounting situation has therefore also an influence on the rate of Na^+-diffusion. So, mounting the modules with backrails might promise to reduce leakage currents. Hence, mounting with module clamps leads to higher leakage currents. Today, state-of-the-art is that the usage of inverters with transformer and grounded negative DC pole in combination with mounting the modules with backrails can avoid the Na^+-diffusion consequently. In contrast to this, the results of newer studies show that the corrosion occurs for positive potentials, too [3, 4]. From the analysis of leakage currents according to the mounting and grounding situation of amorphous silicon solar modules under outdoor conditions conclusions can be drawn about the progression of TCO-corrosion.

In this work, we investigate the influence of positive and negative potentials in respect to leakage currents. Furthermore, the influence of AC potentials regarding leakage currents is shown. The leakage currents will be analyzed for mounting settings with contacted front glass, backrail and module clamps.

2. Experimental

For analyzing the TCO corrosion potential, nine commercially available aSi:H solar modules were mounted on an outdoor test facility. These were superstrate glass-glass modules (i.e. the front and the back enclosure are made of glass). In a first step, the electrical contact was realized by a copper strap on the front glass. At this point, all modules were mounted with module clamps. To carry out the influence of positive and negative potentials, the applied voltages differed between -2000V DC and +2000V DC. Furthermore, one module was used as reference, so no voltage was applied. The specific potential of the modules is shown in Table 1. In this context, the applied potential is always referred to the short-circuited module connectors (i.e. a negative potential means that the negative pole of an external voltage supply is connected to the module connectors). The evaluation of the result of the applied voltage was carried out by I-V-curve measurements. Thus, I-V-curves were measured at the beginning of the test and after one year outdoor exposure and continuous applied potential.

Table 1 Applied voltage of the mounted modules at the outdoor test facility. Module M1a was used as reference module.

Module number	M1a	M2a	M3a	M4a	M5a	M6a	M7a	M8a	M9a
potential	0V	+2000V	+1000V	+600V	+300V	-300V	-600V	-1000V	-2000V

Based on the first experimental step a second measurement sequence was started. The aim of this sequence is to identify the influence of the mounting situation according to the TCO-corrosion depending on the applied external voltage. Furthermore, the effect of AC potentials were investigated. Therefore, three different potentials (-1000V DC, +1000 V DC, 1000 V AC) were applied. Besides, for each type of potential one module was mounted by backrail and two modules were mounted by module clamps. In case of the backrail mounting the potential was applied by an electrical contact at the backrail. One module of the clamp mounting was connected by the clamp and one was contacted by a copper strap on the front glass. In addition, one module was again mounted as reference without any external applied voltage. The leakage currents of each module were measured. Hence, in any module circuit a shunt resistance for measuring the leakage currents was implemented. To avoid disturb signals all cables were shielded and grounded. The voltages over the shunt resistances were measured by a Keithley 2700 digital multimeter with a Keithley 7700 multiplexer card. The measurement was carried out as a differential measurement. Due to this fact, all shunt resistances were placed in the negative part of the circuit of the external voltage supply to ensure that it cannot lead to an overload at the measurement equipment.

Ten leakage currents were measured. For the modules with clamp connection, only the leakage currents between module clamp and the short-circuited module connectors were measured. In the case of the backrail connection, one leakage current between backrail and the short-circuited module connectors and one leakage current between a copper strap on the front glass and the short-circuited module connectors was measured. In addition, for any type of potential one module with just a copper strap connection was monitored, to figure out errors at the combined copper-backrail-measurement. The particular potential of the modules is shown in Table 2.

Table 2 Applied voltage and mounting situation at the outdoor test facility for second test sequence. Module M1b was used as reference module.

Module number	M1b	M2b	M3b	M4b	M5b	M6b	M7b	M8b	M9b
potential	0V	+1000V DC	+1000V DC	+1000V DC	1000V AC	1000V AC	-1000V DC	-1000V DC	-1000V DC
mounting	clamp	clamp	backrail	copper	clamp	backrail	clamp	backrail	copper

3. Results

3.1. First measurement sequence

After a one year outdoor exposure the I-V-curves of each module were measured to figure out the influence of the external applied DC potentials. Each measurement were corrected to the temperature of 50°C. For that purpose a temperature coefficient (TC) for the module voltage of -0.3%/K and a TC for the module current of 0.1 %/K were used. Thereby, the TCs for open and short circuit conditions are the same as for MPP conditions, according to the data sheet. Furthermore, the irradiance is corrected to $1000W/m^2$. All I-V-curve measurements were done directly after the outdoor exposure. Therefore, no light-soaking or dark-period was in between. Module M1a was used as reference with no external applied potential, to separate the influence of outdoor conditions and the external potential. Additionally, it was necessary to determine the differences of the steady state solar simulator; because the measurements after one year were carried out before the simulator was recalibrated. For this reason, all measurements were corrected by adding +3.48% to the I_{sc}.

Fig. 1 shows the differences of the I-V-curves before and after one year outdoor exposure. Fig. 1 (left) represents the changes of the reference module (M1a), Fig. 1 (right) of module M9a, which was exposed to the highest negative potential (-2000V DC). Thus, for this module the highest losses were expected.

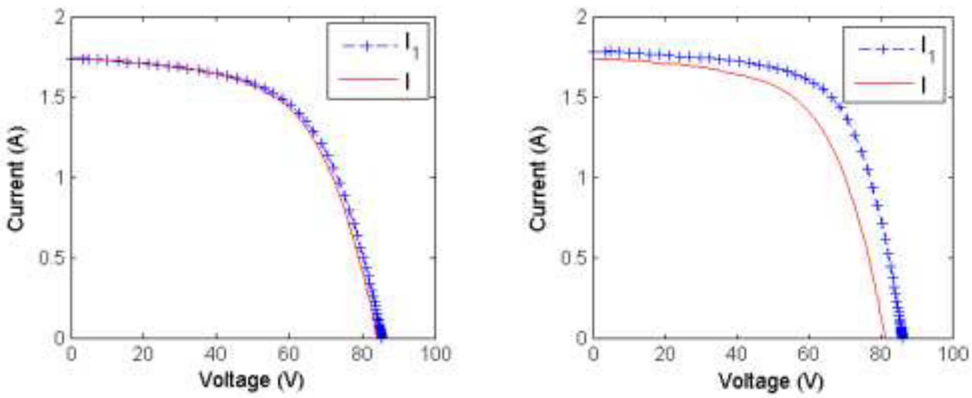

Fig. 1 (left) Corrected I-V-curves of the reference module (M1a) before and after the outdoor exposure; (right) corrected I-V-curves of module M9a (-2000V DC) before and after the one year outdoor exposure. Index 1 denotes the I-V-curve before one year outdoor exposure.

The changes of the fill factor (FF), the maximum-power-point (MPP), the I_{MPP} and V_{MPP}, and of the short-circuit current and open-circuit voltage are depicted in Fig. 2. All the losses are in relation to the initial values, compared to pre-outdoor exposure. For Module M4a with an applied external voltage of +600V DC no results can be defined, as the module broke in the testing field.

Module M9a (-2000V DC) exhibits the highest decrease of all investigated characteristics (Fig. 2). Furthermore, the decrease of V_{MPP} and I_{MPP} is more pronounced than the decrease of V_{oc} and I_{sc}. Therefore, the FF is distinctly affected. The MPP losses are about two times higher. This is in the same

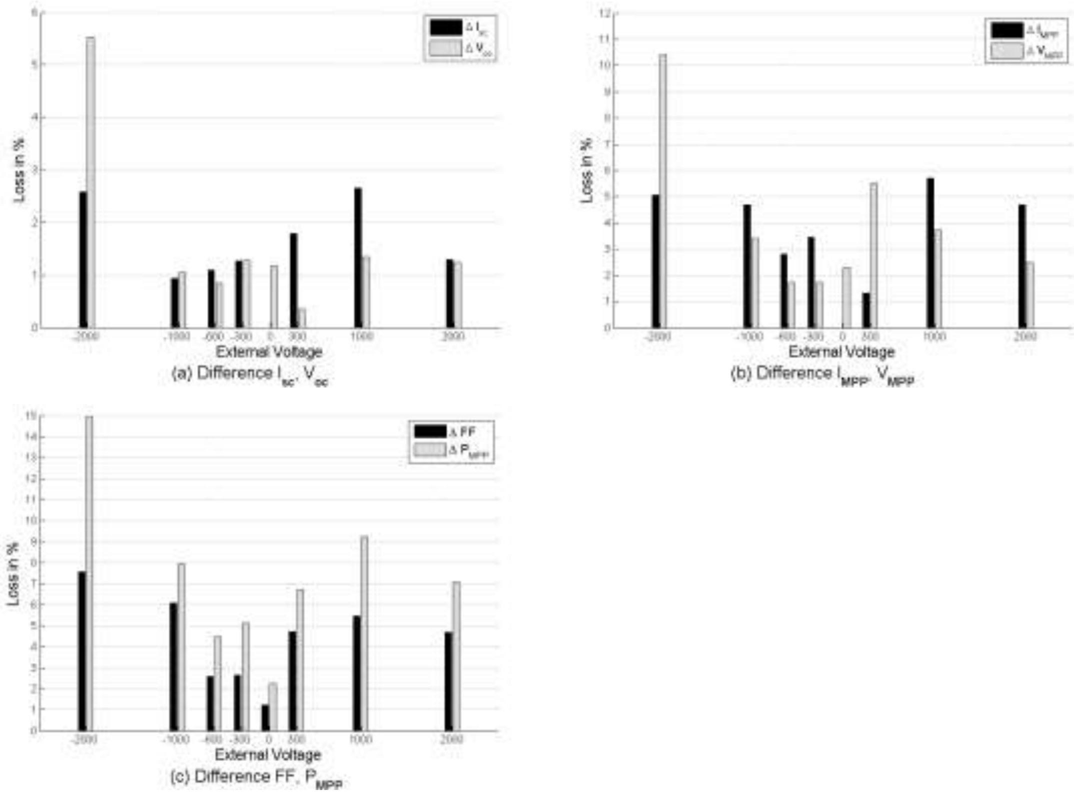

Fig. 2 Difference of all module characteristics before and after the outdoor exposure

range for the other modules, except of M8a (-1000V DC) and M5a (+300V DC). The higher differences can be attributed to partial shading of these modules, which lead to a lot of visible hot spot damages. So the losses for these two modules were higher. The deviations of V_{oc} and I_{sc} are approximately one percent, for the modules which were applied with a negative potential. However, the MPP values decreased considerable stronger. Thus, the module power and the FF decreased considerable, too**.** Moreover, I_{MPP} decrease more than V_{MPP}. For the positive potentials the reductions in V_{oc} and I_{sc} are similar. However, for module M2a (+2000V) and M3a (+1000V) V_{MPP} sank more than I_{MPP}. Whether this behavior is typical for external supplied positive voltages has to be proofed in further investigations. However, the loss of module M2a (+2000V) is smaller than the loss of module M9a (-2000V). In Fig. 2 (c) it is clearly visible, that the power loss of all three modules with applied positive potential exhibit a power loss about five percent. So it can be concluded that a positive potential leads to degradation, too. Note that all modules which were exposed to outdoor conditions do not show any bar graph corrosion, which is described in [1]. The resulting deviations of the I-V-curve measurements are also summarized in Table 3. For the reference module appears also a power loss. Since, there is only a decrease in V_{oc} and V_{MPP} and because no light soaking was done before the test, this can be attributed to the Staebler-Wronski-Effect.

Table 3.Varition of the module characteristics after the outdoor exposure in percent.

	Applied V	ΔP_{MPP}	ΔFF	ΔI_{MPP}	ΔV_{MPP}	ΔI_{sc}	ΔV_{oc}
M1a	0V	2,25	1,23	0	2,29	0	1,175
M2a	+2000V	7,07	4,68	4,69	2,50	1,30	1,23
M4a	+1000V	9,22	5,47	5,70	3,73	2,66	1,34
M6a	+300V	6,74	4,71	1,31	5,50	1,79	0,35
M5a	-300V	5,11	2,645	3,45	1,72	1,27	1,28
M7a	-600V	4,48	2,57	2,81	1,71	1,10	0,86
M8a	-1000V	7,94	6,10	4,70	3,40	0,94	1,02
M9a	-2000V	14,93	7,56	5,05	10,40	2,58	5,53

3.2. Second measurement sequence

The leakage currents induced by negative potentials differ during time in good relation to the environmental conditions. It is generally accepted that this system configuration (negative potential) should represent the worst case for superstrate modules. Subject to theory, the negative potential leads to an accelerated diffusion of sodium ions from the cover glass, which can be measured by leakage currents. The maximum value for the leakage currents is about 12 µA. Note that this value was measured only for one small period. Typically, the leakage currents are less than 0.1 µA for non rain events and rise up to a value between 0.2 and 3 µA for rain events. Anymore, it can be observed that the magnitude of the leakage current depends on the connection method of the module. The backrail connection leads to the lowest leakage currents. Hence, this connection method represents the highest resistance to ground. Furthermore, rain events lead to higher measured leakage currents. In contrast to that, high air humidity values without rain have no significant influence in respect to the backrail connection. In Fig. 3 it is clearly visible, that high air humidity leads not in general to high leakage currents for the backrail connection. Only in case of dew on the module the leakage current rises. The module clamp connection shows a similar behavior. The leakage current through the copper band follows the air humidity well.

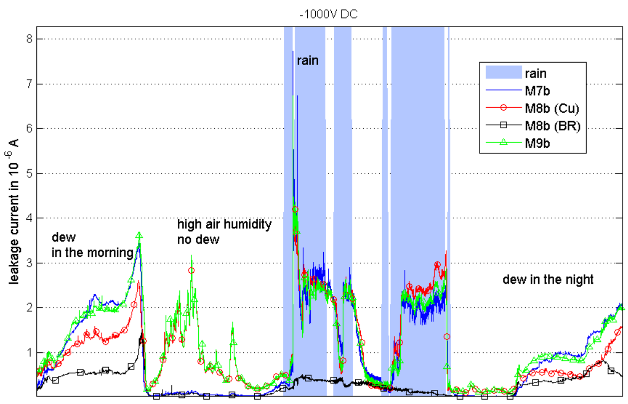

Fig. 3: Results of the leakage current measurement induced by a negative potential of 1000 V DC.

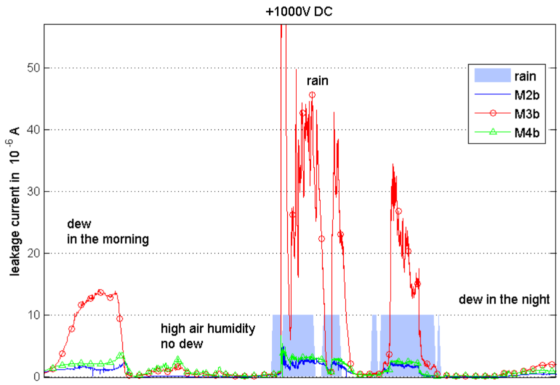

Fig. 4: Results of the leakage current measurement induced by a positive potential of 1000 V DC.

The positive potential leads to a similar characteristic. The magnitudes of the leakage currents also follow the air humidity and the rain events like the negative potential. At the beginning of this measurement series the front glass of module M3b broke. Therefore, humidity could penetrate the module. Because of the superstrate technology no barrier layer is between the glass and the TCO layer. That leads to an extreme boost of the leakage current of this module. The maximum value reaches 340 µA. In comparison to the unbroken modules the maximum value reaches 12 µA. This is similar to the negative potentials. In case of high air humidity with dew on the modules, the leakage current of the broken module is 5 to 6 times higher than for the unbroken modules (Fig. 4). For high air humidity values without dew on the modules the leakage current of the broken module indicates no significant enhancement in comparison to the other modules. However, for rain events it can rise up to 40 times higher than the unbroken modules.

In contrast to the DC potential, the AC leakage currents are over 100 times higher. However, the characteristic is similar to the DC induced leakage currents (Fig. 5). Furthermore, the variation of the magnitude of the AC leakage currents in dependence of the air humidity and rain events is much more pronounced than for the DC currents. Also the influence of the mounting (connection) method can be identified more clearly. The mounting with module clamps (M5b in Fig. 5) leads to a maximum leakage

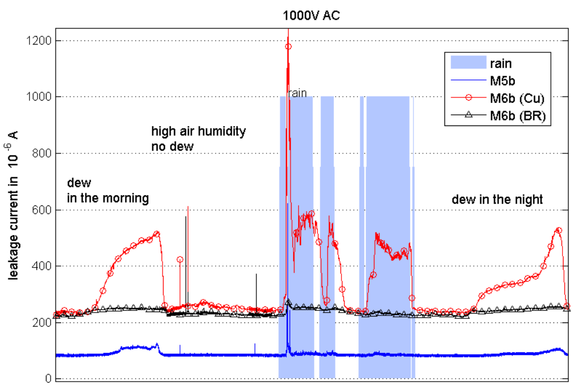

Fig. 5: Results of the leakage current measurement induced by a potential of 1000 V AC.

current of 622 µA. This value is only reached in an extreme rain condition. Typically, the leakage current for this mounting method differs between 75 and 120 µA for non rain conditions and up to 200 µA for rain events. Also it can be observed that the magnitude of the leakage current increases because of an increase of the air humidity which is followed by dew on the module. If there is no dew on the modules an increasing air humidity has no significant influence to the magnitude of the leakage current of module M5b. Module Mb6 is connected only on the backrail. The leakage current was measured between the backrail and the module connectors and between a copper strap on the front glass and the module connectors. In comparison to the mounting by backrail, the leakage current of the copper strap connection is 2.5 times smaller. In case of the mounting by backrail (M6b in Fig. 5) it is not surprising, that the leakage current through the copper contact is more pronounced than the leakage current through the backrail. The ratio between high and low air humidity values is comparable to the measured DC currents, although the absolute value is much higher. Note, in case of the AC potential the resulting leakage currents are all RMS values.

4. Conclusion

As it can be seen from Table 3, the losses of the first measurement sequence differ in all the characteristic values. They depend on the applied external voltage, the higher the bias voltage, the higher the losses. Also, in contrast to many publications, the positive voltage amplified the losses in comparison to the reference module. Nevertheless, these losses were not as high as those stressed with negative voltage (about -15% loss in P_{MPP}).

It seems to be that there is no linear relation between the applied voltage and the losses e.g. of power. What has to be considered is that some of the modules showed more or less optical degradation such as hot spots and scratches. The calculation of the exact influence was not carried out, but under consideration that M3a had for example much more optical degradation than the other modules, the correlation can be assumed as linear, with a much more stronger effect of a negative potential. Therefore it can be said, that a-Si:H solar modules degrade in a PV-generator, when they experience both positive and, with more influence, negative potentials against ground. As expected, the losses of voltage (V_{MPP} and V_{oc}) are, especially for negative potentials, greater than the losses of current. Hence, the series resistance increased, which is dominated by the resistance of the TCO layer. So it can be assumed that the TCO-corrosion process begins, even though no visible bar graph corrosion is detectable, until now.

The results of the second measurement sequence show that there is no significant difference of the magnitude of the leakage currents induced by negative or positive potentials. Of course, the direction of the leakage currents is opposite. Nevertheless, the results of the first measurement sequence have shown that there is also for positive potentials a significant power loss. Consequently, it can be concluded that degradation corresponds with the positive current, too.

The AC potential shows much higher leakage currents than the leakage currents induced by DC potentials. The reason for this fact is probably the module capacity. The impact to the module power in relation to TCO corrosion has to be estimated in further experiment steps.

Overall, the magnitudes of all the leakage currents follow the humidity, even though there are differences for the different contacting methods. Thereby, three distinctive humidity conditions exist: high air humidity without dew on the module, high air humidity with dew on the module and rain events. Only the connection with copper straps leads to an increasing leakage current if the air humidity increases without dew on the module. This can be observed for all three potentials. Hence, this connection method is the most inappropriate variant. Note, for this study there was only one copper strap on the top of the module to simulate a module frame. If there is a real frame the effect could be intensified. For DC potentials the mounting with backrail is the most advantageous mounting method. Although, the leakage currents increase if there is water on the module, the magnitude is much lower than for the mounting with module clamps. On the other hand, for AC potentials the mounting with module clamps leads to the lowest leakage current, even if there is moisture on the module. The reason for this is, that the area which builds the capacity is much smaller than for the other mounting method. Note, that for this study four 20 cm module clamps were used. This leads to a high mechanical stress for the glass. For longtime mounting more or bigger clamps have to be used. So this effect could be compensated if bigger clamps were used. Additional investigations will show the effect on the module degradation of the positive and the AC potential. This can possibly lead to a reassessment regarding the applicability of transformerless inverter in combination with thin film solar modules.

Acknowledgements

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