PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2238

RESEARCH ARTICLE

Effect of humidity and temperature on the potential-induced degradation

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ABSTRACT

This paper focusses on the physical conditions for a degradation mechanism of photovoltaic modules, known as potential-induced degradation. The analysis was made on several levels. At first, the influence of humidity and temperature on the potential-induced leakage current has been investigated, the second step consists of an accelerated test scheme in a climatic chamber and the third one is outdoor exposure with high voltage stress in two different climate regions. The humidity has a huge impact on the leakage current. Therefore, a test in the climate chamber accelerates the stress found in the field of some orders of magnitude. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
high voltage stress; PID; silicon PV modules; accelerated testing

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Received 7 February 2012; Revised 16 March 2012; Accepted 20 April 2012

1. INTRODUCTION

The maximum direct current system voltage of photovoltaic (PV) generators can go up to the limits specified by the manufacturers that might be 600 V in USA and 1000 V (which might be extended to 1500 V in future) in Europe, for example, but depends on the topology of the employed inverter and the grounding. Firstly, a non-reversible degradation of thin-film modules on the basis of a superstrate technology was observed. The degradation mechanism was found to be sodium ion migration from the glass into the transparent conductive oxide (TCO) coating between glazing and solar cell, if the cells had a negative potential against ground [1,2]. The TCO was destroyed. Another high-potential impact is the polarisation effect observed at sunpower cells. These interdigited back contact cells have a negative doped base and positive emitters to maximise the efficiency. Because of this different cell architecture, the polarisation causes an increase of recombination because of negative charges at the anti-reflective silicon-nitride coating. This effect is reversible [3].

The third kind of degradation process is the potential-induced degradation (PID) of crystalline silicon modules, if the cells are on negative potential against ground [4]. This polarity occurs in strings with transformerless inverters with floating ground at the modules with the highest negative bias, which could be up to -500 V when a system voltage of 1000 V was allowed. Worst case would then be -1000 V for grounding the positive pole of the inverter.

High rates of PID were observed when the outer surface of the module became electrically conductive forming the ground electrode against negative cell bias [5–9]. This effect is caused by surface humidity in real operation and can be simulated in climatic cabinets by applying wet cloth or highly conducting layers on the glass panes (e.g. aluminium foils or carbon) paper [10]. The high potential causes a leakage current that might be a measure for the degradation rate [11,12].

2. EXPERIMENTAL SET-UP

Small frameless test modules (four c-Si cells, dimensions 50×50 cm) were used for the lab testing with a self-adhesive aluminium tape as a substitute for the frame, and large 60-cell modules with PID-sensitive cells were produced for outdoor exposure by using the same cells, other module components and lamination procedure. Furthermore, small commercially available modules were purchased.

We used two different high voltage power supplies, which enabled the simultaneous measurements of the leakage current between the short-circuited samples and the frame. Type one has a fixed range for the leakage current (EST-HCDC-K5-USB), whereas the second type covers a broad range of current (iseg NHQ 245 M).

The test modules were mounted electrically isolated in polymer set-up including light sources (Figure 1). The light sources (fluorescence lamps for use in humid environment) were always in operation, when high voltage was applied. Up to eight mini-modules could be exposed simultaneously in the climatic cabinet with the dimensions of $1 \times 1 \times 1$ m. The relative humidity was supplied from the deionized-water circuit and could be controlled between 10% and 95% in the temperature range from 10 to 90 °C.

Two different outdoor test facilities were equipped for weathering tests with high voltage bias. The voltage was only applied between sunrise and sunset.

The Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany, was used for testing the set-up and reference measurements, mainly. The other test site at the Institute for Technology in Canary Islands, Spain, is a place with high wind speed and salt impact. The temperature and humidity levels are different in these locations.

3. THE DEPENDENCE OF THE LEAKAGE CURRENT ON HUMIDITY AND TEMPERATURE

Small test modules (four c-Si cells) were exposed to different temperature/humidity combinations at various bias voltage levels (Figure 2). The leakage current was monitored in the range of microampere (Figure 3).

A second test series was carried out with commercial small modules to investigate the influence of temperature at three possibilities of the grounded electrode with

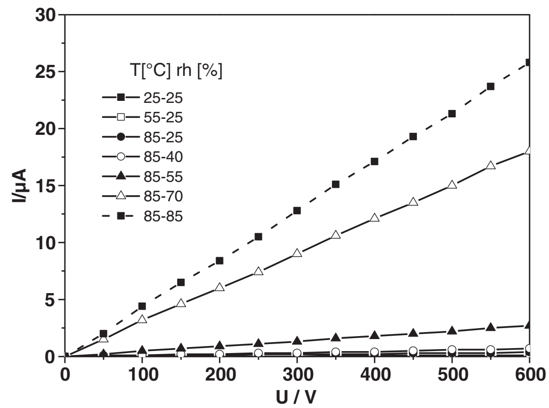

Figure 2. Leakage current as function of the high voltage bias for different temperature/humidity conditions in the climatic cabinet.

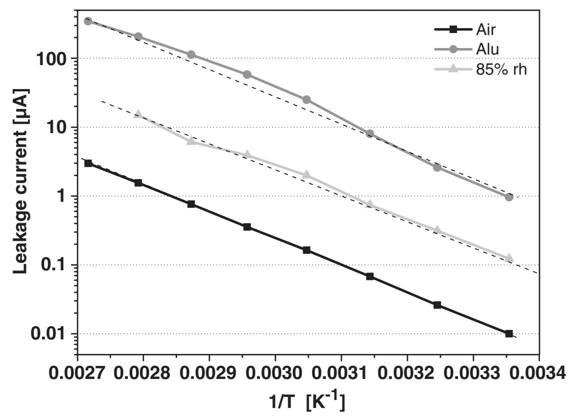

Figure 3. Arrhenius plot of the leakage current at 1000 V negative bias of three identical modules with different methods of contacting: frame only (air), aluminium foil on the glazing (Alu) and damp-heat exposure at 85% relative humidity.

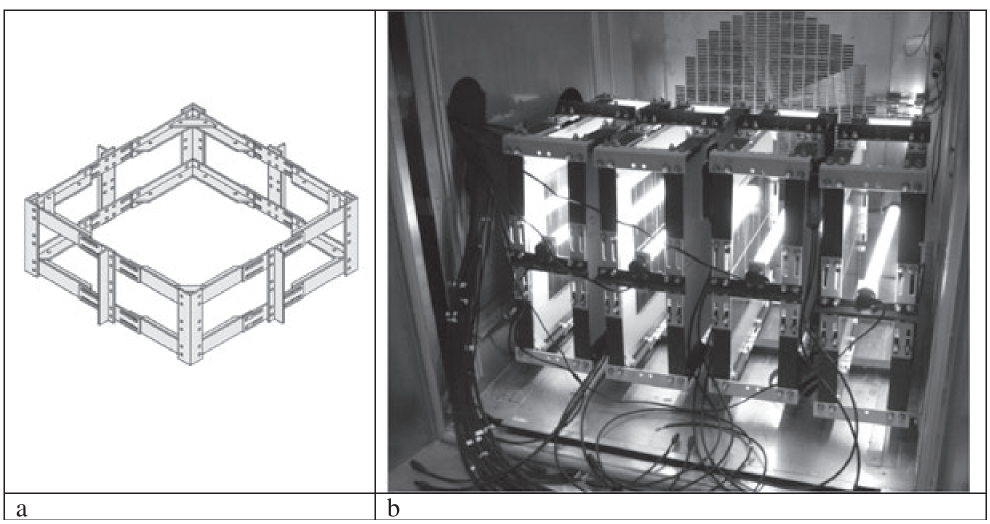

Figure 1. (a) Sketch of the electrically isolated sample holder. (b) Stack of sample holders with 50×50 cm test modules and bias light sources in the climatic cabinet.

negative potential at the cells. One module was exposed to a relative humidity to 85% where the relative humidity formed the electrode via the aluminium frame. A second module had a grounded aluminium foil covering the glazing, and only the frame is grounded in a dry ambience at the third one.

3.1. Dependence on the voltage

Variation of the high voltage at various combinations of temperature and humidity in the climatic cabinet yielded an ohmic behaviour of the leakage current in all cases (Figure 2). A resistivity of 9.4 kΩ was found for the 85% relative humidity at 85 °C conditions. A strong dependence on the humidity could be found. No current was observed if the relative humidity was below 50%.

3.2. Dependence on the temperature

Three commercial mini-modules were used for testing the temperature dependence. The second aim was the investigation of the different ways for contacting the front side of the modules. Table I shows in which conditions the module was used.

The Arrhenius plot (Figure 3) demonstrates that all the processes induced by the voltage either via high humidity or aluminium electrodes have the same kinetics according to an Arrhenius law with activation energy $E_a = 75$ kJ/mol, which is close to the values found previously [12]. The acceleration factor for tests at 85 °C compared with 25 °C is in the order of 160. An acceleration factor f_{ground} of 10 was found changing from air to damp heat and an f_{ground} of 100 for using a conductive aluminium foil as electrode. A total acceleration of 20 000 was found between leakage current at 25 °C in air without additional contact and at 85 °C with the aluminium cover.

Table I. Temperature test conditions for the three mini-modules.

	Ground contact	T	RH
1	Aluminium foil	25–95 °C	Not controlled
2	Air	25–95 °C	Not controlled
3	Humidity	25–85 °C	85%

RH, relative humidity.

The temperature dependence of the leakage current can be described by the following Arrhenius relation with Boltzmann constant R:

$$I_{test} = I_{ref} \cdot f_{ground} \cdot \exp\left[-(E_a/\ \mathrm{R}) \cdot (1/T_{test} - \ 1/T_{ref})\right] \quad (1)$$

By using $T_{ref} = 85$ °C in air as reference conditions for an investigation of a module with an area resistivity $\mathrm{R_a}$ and an Area A,

$$I_{test} = U/\ \mathrm{R_a}(358\ \mathrm{K}) \cdot A \cdot f_{ground} \exp\left[-(E_a/\ \mathrm{R}) \cdot (1/T_{test} - \ 1/358\ \mathrm{K})\right] \quad (2)$$

These commercial modules did not show any PID in spite of the leakage current in the same order of magnitude as the other PID-sensitive modules.

3.3. Dependence on the humidity

The leakage current between frame and cells depends on the ambient humidity on one hand. This humidity forms a film on the glazing, which starts to become electrically conductive after a percolation threshold of about 60% (Figure 4). This character can be modelled with a sigmoidal growth function, which approaches a maximum current I_{max} for complete wetting at 100% relative humidity:

$$I = I_{max}/(1 + (I_{max}/c - 1)/\exp(I_{max} \cdot (rf - a) \cdot b)\ ) \quad (3)$$

$I_{max} = 13.2$ µA for 300 V (Figure 4). Because of the ohmic behaviour (Figure 2), we can assume that

$$I_{max} = U/\mathrm{R_a} \cdot A \quad (4)$$

where A is the area of the module and $\mathrm{R_a} = 570$ ohm/cm² for the investigated mini-modules. The resistivity depends on the module types.

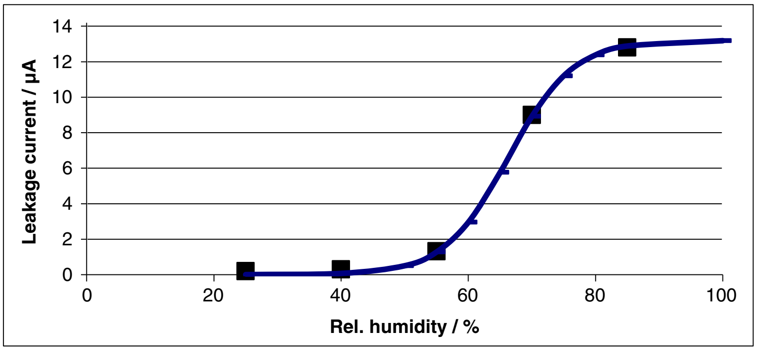

Figure 4. Leakage current as function of the relative humidity at 85 °C in the cabinet at 300 V negative bias. The squares are measured values, and the curve is the result of a simulation with Equation 3.

The remaining parameters $a = 0.3$, $b = 1.5/\mu A$ and $c = 0.3\ \mu A$ describe the slope of the current increase and the offset.

3.4. Modelling of the leakage current

Combining the models for temperature and humidity dependence yields a general model for the leakage current as function of temperature, humidity and voltage, which could be helpful for the outdoor stress estimation:

$$I = I_{max}/(1 + (I_{max}/c - 1)/\exp(I_{max} \times (rf - a) \times b)) \quad (5)$$

with

$$I_{max} = U/R_a(358\ K)\ A \cdot \exp[-(E_a/\ R) \cdot (1/T_{test} - 1/358\ K)] \quad (6)$$

4. OUTDOOR TEST RESULTS

A constant voltage of 600 V or 450 V was applied between sunrise and sunset. Module temperature and leakage current have been measured during this time too. The modules were kept near to their maximum power point with resistive loads.

The importance of a high relative humidity can be seen at the outdoor data shown in Figure 5, which was monitored during the exposure in Freiburg, Germany [13]. High leakage currents occur at a high level of relative humidity. It is important to consider the role of the temperature. Usually, the temperature will increase the leakage current as demonstrated in Section 3.2. But Figure 5 shows that the increasing temperature of the PV module leads to a low relative humidity on the module surface and therefore to a low leakage current. Figure 6 shows the same data in a different way. The leakage current is plotted as function of the relative surface humidity of the module.

After sunrise, the module is heated by the solar radiation, and the increasing temperature actually decreases the humidity in the microclimate of the module (Magnus formula), and therefore, the contacting gets worse, which results in a linearly decreasing leakage current. A constant current remains for some time, which might be attributed to humidity in the encapsulation. The current goes down to practically zero till sunset, when the module cools down and starts getting humid again. Therefore, the morning hours are the most hazardous conditions for PID at sunny days, so far.

But a second phenomenon could be identified. The leakage current was increased by two orders of magnitudes in case of rain, as shown in Figure 7 where the leakage current of the same module is plotted at two different days. The high leakage currents were observed on 18/06/2011 with a few hours of rain in the morning. After the rain stopped, the leakage current immediately dropped down to a level, which was observed at days without rain events such as 09/06/2011.

The amount of leakage charge on a day with 4 h of rain was 53 times higher in case of module M17 and 29 times higher for module M18 compared with a sunny day (Figure 8). The impact of rain events on the leakage current is very important because of the very good conductivity of water and has to be taken into account when the progress of PID during outdoor exposure is evaluated for development of appropriate service life tests.

5. COMPARISON BETWEEN INDOOR AND OUTDOOR

It seems to be obvious that leakage currents are a condition for PID, but leakage currents are not sufficient for

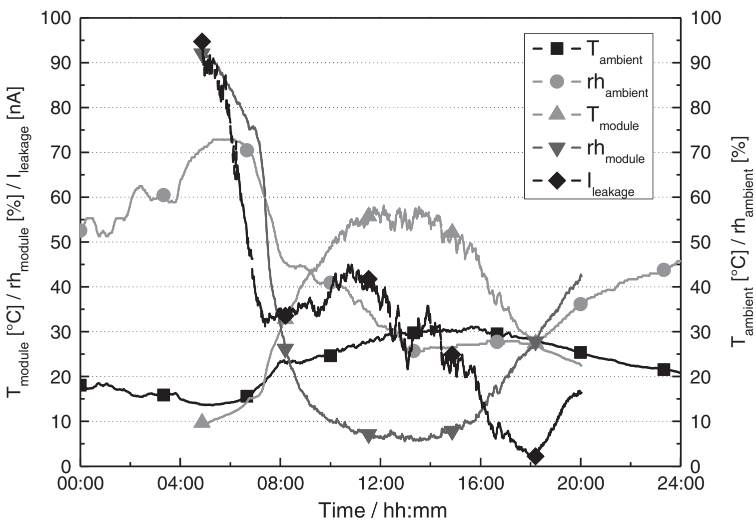

Figure 5. Ambient weather data (temperature, humidity) and microclimate data (module temperature, module humidity and leakage current at 600 V bias) at a sunny day in Freiburg, Germany.

DOI: 10.1002/pip

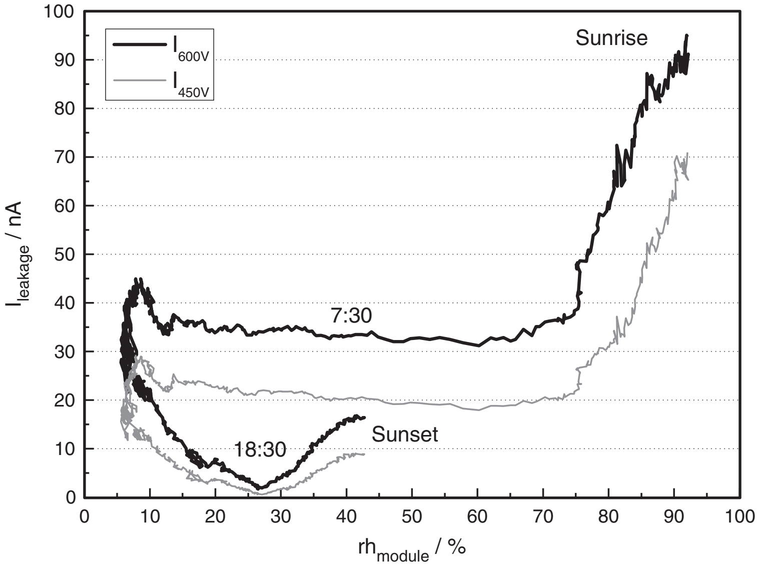

Figure 6. Leakage current as function of the module surface humidity during one day for two modules with different bias voltage (450 V (grey) and 600 V (black)).

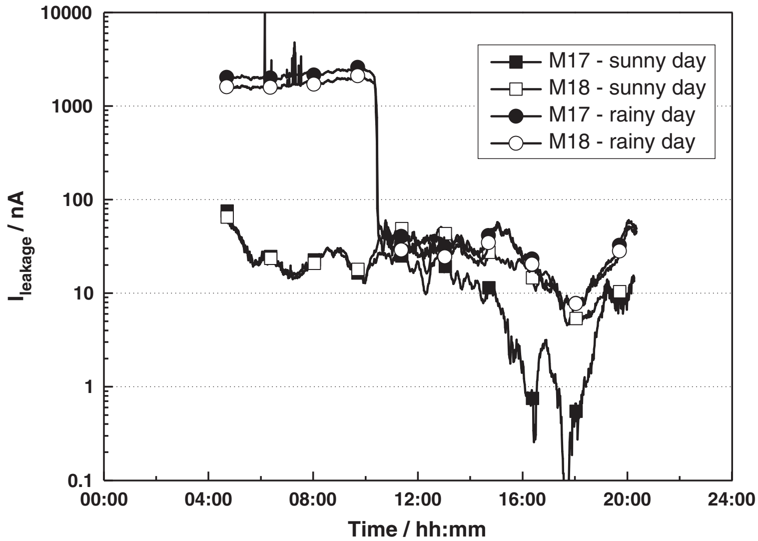

Figure 7. Leakage current as function of the time for one rainy day (dots) and one sunny day (squares) for two modules with different bias voltage of 600 V direct current (M17) and 450 V direct current (M18).

PID. At least, they can be helpful for the comparison of natural operating conditions and lab testing. JPL once proposed to use the integrated charge as a measure for module damage risk. This charge might be useful for assessment of the PID progress during testing. Figure 9 shows the cumulative charge observed at outdoor testing and the accelerated indoor test.

The accumulated charge after 100 days was about 10 times higher in Grand Canary compared with Freiburg. The reason could be the higher humidity level in Grand Canary or the stronger soiling because of the shore nearby and the higher temperature level. A longer integration period would be needed for a serious comparison.

The accelerated tests at damp-heat conditions (85% relative humidity at 85 °C) yielded a cumulated charge that was eight orders of magnitude higher after 10 days (the test modules had lost performance completely) and six orders of magnitude higher than the exposure in Canary Island after 100 days. The PID can be accelerated very strongly by constant load tests, when no regeneration during night time is taken into account.

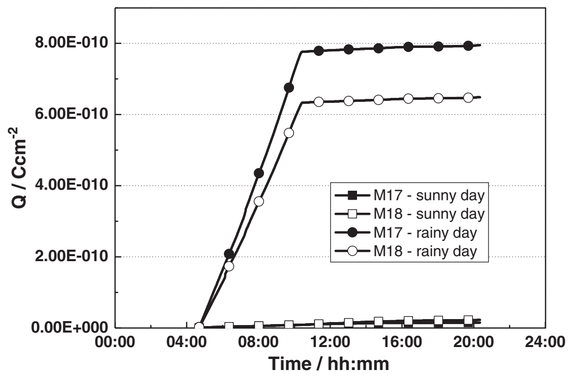

Figure 8. Integrated leakage current as function of the time for one rainy day (dots) and one sunny day (squares) for two modules with different bias voltage of 600 V direct current (M17) and 450 V direct current (M18).

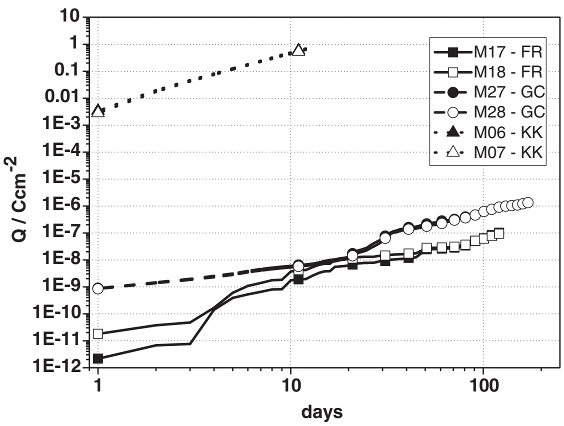

Figure 9. Cumulated leakage current as function of the time for exposure in Canary Island (circles and points), Freiburg (squares and straight line) and during damp-heat testing (85% relative humidity at 85 °C) (triangles and dashed line) for always two modules with different bias voltage of 600 V direct current (solid symbols) and 450 V direct current (open symbols).

6. SUMMARY AND CONCLUSIONS

The impact of temperature, humidity, bias voltage and contact to the ground on the leakage current was investigated with mini-PV modules. The temperature dependence obeyed an Arrhenius relation with an activation energy of 75 kJ/mol. The correlation with the bias voltage showed an ohmic behaviour. The leakage current was a factor of 10 lower without high surface humidity but a factor of 10 higher with a contacting metallic foil on the glazing. The correlation with the ambient humidity could be modelled. This model might be helpful for the evaluation PID of outdoor exposed and monitored modules. First results depending on the ambient climate could be reported. A surprisingly high contribution to the cumulated leakage current was found at rainy days.

The leakage current or the integrated charge seems to be a good indicator for possible PID but might not be necessarily sufficient. Further work will focus on the investigation of the impact of the properties of the module components, cells, encapsulates and back-sheets especially and on the modelling of the outdoor behaviour.

ACKNOWLEDGEMENTS

The authors are grateful to Christian Schill and Stefan Brachmann for their help in setting up the high voltage testing and monitoring and to Q-Cells for providing especially prepared PID-sensitive samples.

The work was partly funded by the German Federal Minister for Education and Research BMBF (FKz 03SF0337C) and the company Q-Cells SE.

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