MODELING POTENTIAL-INDUCED DEGRADATION (PID) IN CRYSTALLINE SILICON SOLAR CELLS: FROM ACCELERATED-AGING LABORATORY TESTING TO OUTDOOR PREDICTION

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ABSTRACT: We present a mathematical model to predict the effect of potential-induced degradation (PID) on the power output of c-Si modules in different climates. For the experimental part, we manufacture mini-modules made of two c-Si p-type cells, and use accelerated ageing laboratory testing performed at different combinations of stress factors (temperature, relative humidity, and voltage). By modeling the effect of each stress factor in a step-wise approach, we obtain a model for the PID at constant stress conditions, which agrees well with models that can be found in the literature for full-size modules. Our model is obtained complementing existing models by introducing a term that describes a linear dependence of module's power degradation on the magnitude of the applied voltage. Since in field installations PV modules are connected in strings and exposed to different potential – and, therefore, stress – levels, this latter term is needed to approach real field conditions. Finally, we present the first attempts to model PID outdoor degradation in different climate conditions based on the proposed model and on the indoor-determined coefficients for the devices tested. The outdoor prediction model makes use of Typical Meteorological Year (TMY) data for a specific location.
Keywords: Potential induced degradation, PID, Modeling, Lifetime, Crystalline silicon

1 INTRODUCTION

Predicting lifetime and power delivery over time of photovoltaic (PV) modules in real outdoor conditions is essential to all stakeholders. During their operational life, modules are exposed to a variety of stresses that can degrade their performance, the exact type of degradation depending on the module technology and the climate where the modules are operating. One particular degradation mode is potential-induced degradation (PID), which is increasingly evident not only in tropical climates but also in temperate ones (as e.g. in Germany, [1]). Results published in the last few years about accelerated tests on commercial modules gave evidence that commercial modules presently on the market can be prone to large levels of degradation. This was confirmed by other authors showing that even modules sold as "PID-free" fail the proposed standard test with power losses of up to 50% (see [2]). For all these reasons, a more extensive investigation on PID is required to assess its impact on modules lifetime.

In the last few years different models were proposed to simulate field power degradation due to PID. Some authors (e.g. [3], [4], and [5]) based their approach on the modeling of the shunt resistance, derived from laboratory testing in climatic chamber first, and then simulating its evolution in outdoor conditions. In other studies (such as [6] and [7]), empirical equations for the power loss were deduced from accelerated testing in climatic chambers and then used in combination with climatic data to simulate outdoor degradation. Here, we performed accelerated PID tests on 2-cells mini-modules at different stress levels (temperature, relative humidity, and voltage), from which we developed an empirical mathematical model that describes the power degradation. Such degradation model is mainly based on the one introduced by Hacke et al in [8], where in particular the power loss is described with a parabolic behavior over time. We further complemented this model with the introduction of a term describing the linear dependence of the degradation mechanism on voltage. The impact of different encapsulants is assessed by comparing results of accelerated tests on EVA (ethylene vinyl-acetate) and TPO (thermoplastic polyolefin)-based samples. In a second step, we propose an implementation of such model in outdoor conditions using typical meteorological year (TMY) data as input parameters, giving a first approximation of PID-related power degradationin different climates.

2 PID

Different types of PID occur depending on the module technology. A polarization-induced degradation was described in [9] for back-contacted (Sunpower) modules. They discovered the so-called "surface polarization effect": when n-type cells operate at high positive voltage towards ground, negative charges accumulate in the SiN_x antireflective layer increasing the front surface recombination, and consequently enhancing the recombination of the photo-generated carriers. This mechanism was proved to be reversible by, for instance, making the cells operating at negative voltage towards ground. For conventional c-Si cells, a similar phenomenon involving an ionic transport between the solar cells and the module frame through the front glass and encapsulant leading to modules' power degradation is in some cases observed as well (see [10], [11], [12] among others). In the case of conventional p-type cells, a negative voltage towards ground drives positive ions (predominantly sodium Na^+) from the front glass towards the solar cells. Here they can affect cell performance not only by increasing surface recombination [13], but also by migrating to stacking faults in bulk silicon that may potentially intersect the junction and lead to shunt creation [14].

PID depends on the polarity (i.e. conventional p-type cells are affected by negative voltages only) and on the magnitude of the potential applied between cells and ground [11]. It is also clearly linked to environmental factors as relative humidity [12] and temperature [15]. Moreover, it depends on the cell or module design and material properties, such as the conductivity (or Si/N ratio) of the anti-reflective coating [16], the resistivity of the encapsulant [17], or the presence of a module frame.

3 EXPERIMENTAL WORK

Two cells mini-modules (with a size of20 × 40 cm) were laminated at EPFL PVLAB. All samples feature the same cell type, commercial mono crystalline silicon p-type cells with a single p-n junction. We employed two encapsulation schemes, glass/glass (G/G) and glass/backsheet (G/B),with the same soda-lime glass for all samples and the same polyethylene-based backsheet for G/B samples. Two different encapsulants were used in the encapsulation process: an EVA and a TPO. The metallic frame was simulated by means of an electrically conductive aluminum tape, (see [18]). Accelerated aging tests were then performed in a climatic chamber according to the procedure described in the proposed IEC Technical Specification for PID in c-Si modules (IEC TS 62804-1:2015). In order to model the contribution of the various stress factors, we varied the stress levels in each test, as illustrated in Table 1. Moreover, we extended the tests duration to 192h, twice as much the prescribed time of 96 h. The voltage levels refer to the potential difference of the module's cells with respect to the grounded frame.

Table 1 Accelerated-aging testing conditions to investigate PID dependence on temperature T, relative humidity RH, and voltage V. Tests at 85°C/85% RH were repeated with additional voltage levels of -600 V, -400 V, and -200V. Duration of all tests was 192h.

	V=-1000 V			
T / RH	**65%**	**75%**	**85%**	**95%**
45°C				
60°C				
75°C				
85°C			V=-200V V=-400V V=-600V	

The electrical characterization of the mini-modules was performed at standard test conditions (STC: AM1.5G, 25°C, 1000W/m^2) by means of current–voltage (IV) characteristics using a LED-halogen based sun simulator. Mini-moduels were tested (i) prior to climatic chamber testing, (ii) at an intermediate stage of 96h, and (iii) after 192h.

3.1 Leakage current

The leakage current measured between the frame and the cells was proposed by some authors as a possible measure of PID ([18], [5]). However, some studies ([19], [20]) proved that a leakage current increase cannot always be directly correlatd to modules' power loss. Results of our tests also proved this lack of correlation, as shown in Figure 1. Therefore, even though leakage current is representative of the accumulated positive charge on the cell, it is not a good indicator for PID, and we consequently chose the mini-module maximum power as more suitable parameter to model PID.

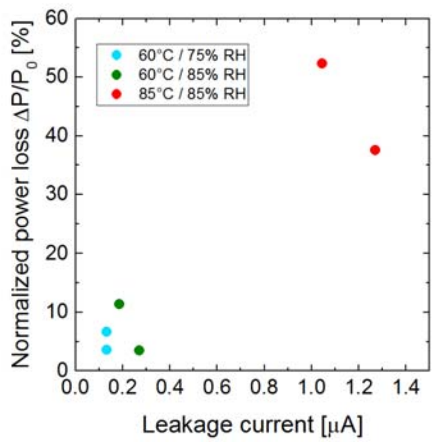

Figure 1 Power loss after 192h of PID test, for G/B samples with EVA, versus leakage current (obtained as the average of the leakage current measured all over the test duration): no correlation is observed.

In agreement with what previously found by other authors such as [10], [12], and [18], we observed that leakage current follows an Arrhenius behavior with respect to temperature, with an activation energy of 0.69 eV. This value is similar to values previously published in the literature (see [7]). Instead, the absolute values of leakage current are lower to theirs considering that they were testing 1-cell mini-modules. Values up to 10 times higher were reported by [18] for their 4-cells mini-modules with aluminum frame: such a difference can be attributed not only to the different number of cells, but to the use presumably of a different type of encapsulant too.

3.2 Encapsulant influence

It is known that PID can be minimized at module level by using an encapsulant material that reduces the transport of sodium ions ([11], [21]). In Figure 2 the performance of G/G samples with the two different encapsulants is shown.

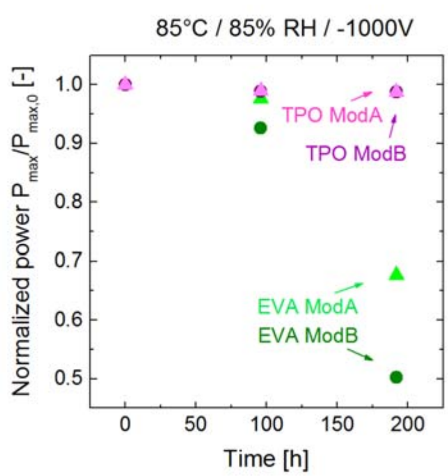

Figure 2 Power time-evolution of four G/G mini-modules tested at 85°C / 85% RH / -1000V Samples with EVA degraded more than those with TPO. The points for the two TPO samples are overlapped.

A significant degradation is observed for EVA-based mini-modules, where a standard commercial EVA was used. On the other hand, samples with TPO showed very good resistance to PID also under harsh test conditions such as 192h at 85°C/85% RH. The better performance of TPO is attributed to its higher electrical resistivity and better resistance to water ingress, as for instance given by the water vapor transmission rate (WVTR). These properties are listed in Table 2.

Table 2 Properties of the EVA and TPO employed in PID tests on mini-modules. WVTR stays for Water Vapor Transmission Rate.

	WVTR [g/(m^2·day)]	Water absorption [%]	Volume resistivity [Ohm·cm]
EVA	15-25	~0.04	>1·10^{15}
TPO	<5	<0.01	>2·10^{16}

To investigate TPO's long-term performance, we plan to extend the duration of the testing for samples laminateed with this material. Here, with the purpose of developing a model for PID, we restricted our attention to EVA that is still the mostly used encapsulant in PV. Moreover we focused our attention on mini-modules with G/B construction as more representative of the PV industry for c-Si modules.

4 PID MODEL FROM LABORATORY TESTING

In this Section we use a step-wise approach and present the mathematical description of each stress factor's contribution to the modules's power loss. First, this brings to the validation of the degradation equation given by Hacke in [8]. Then, the contribution of voltage is added.

Each point in the following plots represents the average of measurements performed on a number of samples, which varies from two to four samples, depending on the test conditions.

4.1 Temperature

As documented in several studies, [20] among others, temperature is one of the degradation factors for PID, mostly under humid conditions. Indeed, high temperature promotes ion migration from the glass to the cell as a result of an increased electrical conductivity of both the glass surface and the encapsulant material. The experimental tests performed in this work show an Arrhenius dependence of the power loss on temperature (see Figure 3). The activation energy we derived for the power loss is 0.86 eV.

4.2 Relative humidity

A complete description of PID requires modeling the effect of relative humidity on the power loss. Monitoring of modules in outdoor conditions [18], [22] showed a strong degradation during periods of high relative humidity, when the surface's glass conductivity increases making the glass surface nearly equipotential to the frame. As an example, a relevant reduction in shunt resistance together with high values of leakage currents were in fact obeserved in [22] during the mornings, when water condensates on the module surface, and during rainy days. In this work, tests performed in climatic chamber at different relative humidity levels suggest a polynomial behavior of the power loss with respect to RH, as depicted in Figure 4.

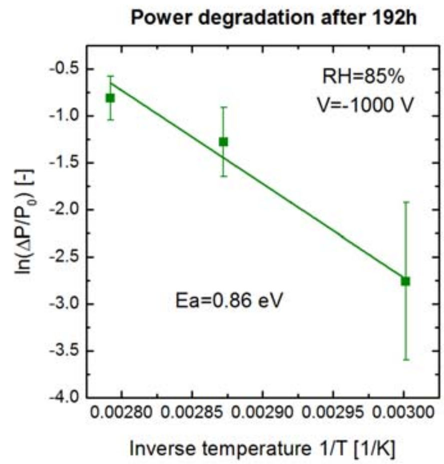

Figure 3 Normalized power loss for G/B mini-modules with EVA after 192h of PID test at 85% of RH and -1000V applied: an Arrhenius behavior with respect to temperature is deduced, with an activation energy of 0.86 eV.

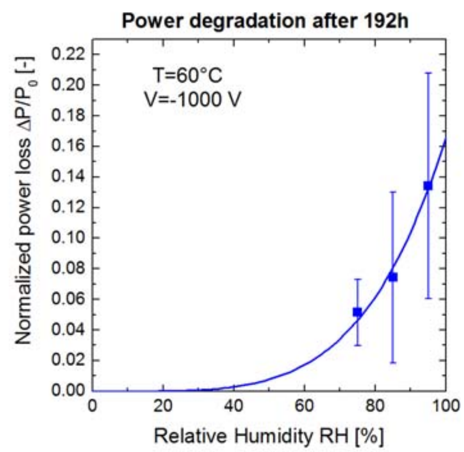

Figure 4 Normalized power loss for G/B mini-modules with EVA after 192h at 60°C and -1000 V exhibits a polynomial dependence on relative humidity.

4.3 Time

As mentioned, mini-modules IV characterization was performed after 96h and 192h in climatic chamber. In agreement with what found in [8] for commercial modules, the evolution of the maximum power of our mini-modules is quadratic in time, in our case during the first 192h, as shown in Figure 5. Tests at longer duration are planned to verify if such parabolic behavior still gives a good description of power evolution on longer time scales.

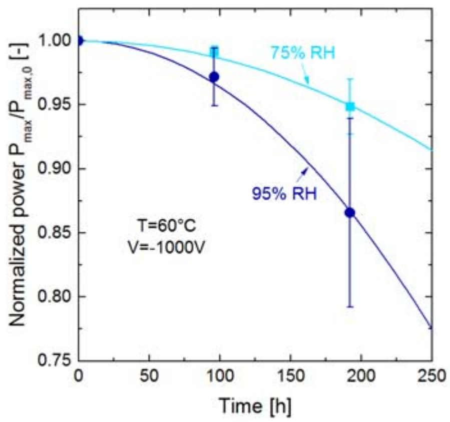

Figure 5 Evolution in time of maximum power for some of the test conditions performed: the behavior in the first 192h can be fitted with a quadratic curve.

The models for the contributions of the stress factors discussed above (temperature, relative humidity, and time) were introduced by Hacke in [8], who proposed equation (3) in the reference to describe power degradation during accelerated tests at constant T and RH conditions with an applied constant voltage of -1000V. Sections 4.1, 4.2, and 4.3 provided further experimental validations of this model as a good agreement was found with results of accelerated tests on our 2-cells mini-modules. In the next section, we introduce a term assessing the impact of voltage on the PID effect.

4.4 Voltage

Several inspections on PV plants (e.g. [11]) clearly indicate that, for modules made with conventional p-type cells, the degradation of modules within a string is stronger when moving towards higher negative potentials with respect to ground. This latter term is, therefore, needed to approach real field conditions, as field PID degradation will depend on the module's position within the string.

Here, we performed tests at several voltage levels and observed that the power losses at a fixed time (e.g. after 96h) vary linearly as a function of the applied voltage, as Figure 6 shows.

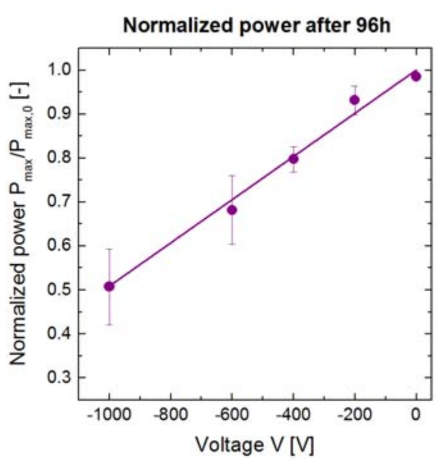

Figure 6 A linear behavior is observed for maximum power after 96h of PID tests as a function of the voltage.

We finally bring together the effect of all distinct contributions and propose a simplified relation (Eq. (1)) describing the power degradation as function of PID at constant stress test conditions:

$$\frac{P_{max}(t)}{P_{max}(0)} = 1 - C_V \cdot V \qquad (1)$$

where $P(t)$ is the modules' measured power after t hours of exposure to constant stress levels, $P(0)$ is the initial power, and C_V is a coefficient, which includes the effect of temperature, relative humidity, and time *t*. The coefficient C_V represents the equation previously proposed by Hacke et al. in [8], recalled hereunder in the form of Eq. (2), where κ is the Boltzmann constant.

$$C_V(T, RH, t) := A \cdot e^{-\frac{E_a}{\kappa T}} \cdot RH^B \cdot t^2 \qquad (2)$$

By fitting Eq. (1) for our mini-modules, we obtained the following values for the parameters: A=6.0188·10^{-5} h^{-2}, B=4.43 [-], and E_a=0.86 eV as pointed out in Section 4.1. One should notice that the parameter E_a is interpreted here as the activation energy of the power loss. Other authors concentrate, instead, on the activation energy of the time to reach a certain level of power loss (let us call it the "time-to-failure"). One can check that Eq. (1) and (2) imply in particular that the activation energy of the power loss is twice the activation energy of the "time-to-failure". Values reported by Hacke in [8] and Raykov in [7] are 0.85 eV and 0.75 eV respectively: this would therefore mean an activation energy of 1.7 eV and 1.5 eV for the power loss. We conclude that the value of 0.86 eV obtained by us is lower compared to the mentioned references. Reasons for this might lie for instance in the particular type of encapsulant employed or in the samples configuration. This will be subject of further investigations.

We are currently subjecting samples to experimental work (and different combinations of temperature and irradiance) to model a regeneration term for the PID phenomenon. Regeneration is in fact generally experienced by degraded modules when stored under controlled laboratory conditions or can be experienced by modules in the field. This part is not presented here and will be subject of a future contribution.

5 SIMULATING OUTDOOR PID DEGRADATION

The model presented in Eq. (1) describes the power degradation due to PID at constant stress laboratory conditions.

In this section, we attempt to describe what the power degradation of mini-modules would be, if they were installed at a constant negative voltage (-1000 V) in sites representative of different climatic conditions (Riyadh = Hot and Dry, Sigonella (Sicily) = Mediterranean, Miami = Hot and Humid). To do this, we use the coefficients of the distinct ageing contributions (temperature, relative humidity and time) as determined in Section 4 by means of indoor laboratory testing.

Using Eq. (1) and (2) and the indoor determined parameters to model outdoor PID degradation is, however, not straighforward. Firstly, because stress conditions outdoors are not constant. Secondly because, whereas indoors module's power undergoes a continuos degradation described by Eq. (1) and by a fixed initial power value $P_{max}(0)$, outdoors the module power $P_{max}(t)$ at time t fluctuates continuosly depending on irradiance, module's temperature and other environmental parameters.

For the different locations, to model the istantaneous power $P_{max}(t)$ of the devices, we use Typical Meteorological Year (TMY) data from Meteonorm with time-resolution of 1 hour as input weather parameters and PV_LIB Toolbox for Matlab (from Sandia National Laboratories). A c-Si glass/backsheet module was considered, with open-rack configuration. The degradation Eq. (1) was then applied in an iterative way, taking as stress factors at each time-interval $[t_i, t_{i+1}]$ the instantaneous temperature T_i and relative humidity RH_i values and supposing a constant voltage of -1000 V over daylight. No degradation was applied during the night and no regeneration was considered. First results are shown in Figure 7.

In order to make the implementation consistent, per each time interval the starting point on the degradation curve was calculated as the equivalent time needed at temperature T_i and relative humidity RH_i to reach the level of degradation of the previous time-step $[t_{i-1}, t_i]$. A similar approach has previously been applied by [5]. For the first time-interval of each day, the starting point was defined as the equivalent time to reach the average degradation level of the previous day (this choice is responsible of the non monotonously decreasing behavior of the normalized power that can be observed in Figure 7). This methodology for implementation differs from that by Hattendorf [6] in particular in the power loss equation, in the method used to estimate $P_{max}(0, i)$ and because it makes no use of threshold values for RH to trigger a degradation.

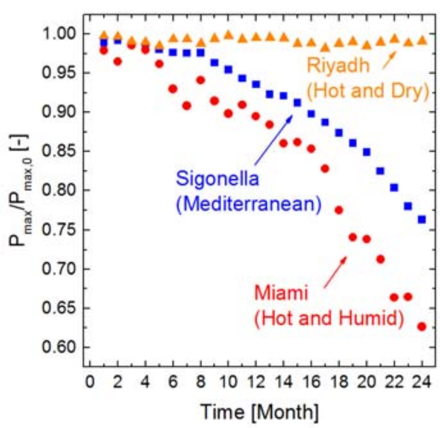

Figure 7 Simulated evolution of maximum power of a module in three different climates as consequence of the degradation mechanism of PID.

As mentioned, what we present here are the first attempts to model outdoor degradation of PID-affected modules. In fact a regeneration term is still missing from the model. As shown in other studies, ([15], [23]), in real outdoor conditions the effect of PID is a continuous trade-off between a degradation and a regeneration mechanism, which may occur for example during hot dry periods. Some models have been proposed for the regeneration mechanism ([6], [3], [7]). At the same time, we are collecting data from different PV plants in order to validate this model.

The possibility to manufacture and work with mini-modules carries considerable advantages: the manufacturer process is flexible, relatively fast and cost-effective, and we can vary materials (encapsulant, baksheets, glass) and cells properties. On the downside, extending the results obtained on mini-modules to large-area modules is not always straightforward and may require some adjustment to the model. This has been the object of recent analyses, where for example in [24] it was shown that in desert climates the degradation typically occurs only in the edge cells, while a more homogeneous degradation pattern can be observed in humid climates due to increased surface's glass conductivity.

6 CONCLUSIONS

Laboratory PID testing was performed on 2-cells mini-modules at several stress conditions. On the one hand, tests results suggest that mini-modules behavior can be described by the model that Hacke et al developed in [8] for commercial modules. On the other hand, we added to their power loss equation a term that describes the dependency of degradation on voltage, obtaining Eq. (1). Such equation, which describes the power loss at constant stress conditions, was then used to model outdoor PID degradation for different climates. To do this we use the indoor determined coefficients of the distinct ageing contributions (temperature, relative humidity and time) and use TMY data to model the power in operation of outdoor exposed modules in different locations. A strong influence of the climate is evident in simulations results where, as expected, a more severe degradation is predicted for hot and humid climates. Such simulations give a preliminary approximation of the time-evolution of power performance and are not complete yet as they do not consider the contribution of power recovery. Experimental work to model the regeneration as function of the climate factors is ongoing, as well as accelerated testing on commercial modules of different manufacturers. Future work will include investigation of any discrepancy between mini-modules and full-size ones, and of how to take this into account in the model.

In parallel to this experimental work, field data are collected in order to provide a validation of our simulations.

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