preprint to be published in the proceedings of the
29th European Photovoltaic Solar Energy Conference, 22-26 September 2014, Amsterdam, Netherlands

POTENTIAL INDUCED DEGRADATION: MODEL CALCULATIONS AND CORRELATION BETWEEN LABORATORY TESTS AND OUTDOOR OCCURRENCE

Christian Taubitz*, Matthias Schütze, Marcel Kröber, Max B. Koentopp
Hanwha Q CELLS GmbH
Sonnenallee 17-21, 06766 Bitterfeld-Wolfen, Germany
*corresponding author: c.taubitz@q-cells.com, +49-(0)3494-6699-52162

ABSTRACT: Potential induced degradation (PID) is a critical failure mode in today's photovoltaic (PV)-system architecture with very large to catastrophic impact on PV-module performance and energy yield. Potential-induced shunting (PID-s) is one of the most severe types of PID leading to shunting of p-type silicon solar cells. Previously, the kinetics of PID-s was investigated in detail. It was shown that shunting and regeneration from PID-s are Arrhenius-like. Based on this finding a preliminary model was developed.
In this work the PID-s model is presented in more detail. The model employs meteorological data and measured shunting and regeneration kinetics in order to estimate the actual PID-stress a fielded PV-module is submitted to during its lifetime in a specific location. Using the model, the outdoor occurrence of PID-s depending on location and module-type can be predicted. Outdoor-measurements of PID-s progression in the field are shown and compared to PID-s model-simulations in order to validate and improve the simulation results.
Keywords: Degradation, Module, Reliability, PID

1 INTRODUCTION

In modern photovoltaic (PV)-system architecture solar cells incorporated into PV modules can be exposed to a voltage bias of several hundred volts with respect to the grounded module frames. This voltage bias can cause various kinds of degradation, which are commonly termed potential-induced degradation (PID) [1]. One of the most severe types of PID is potential-induced shunting (PID-s) leading to shunting of p-type silicon solar cells [2][3]. Due to the high impact on module performance an understanding of the risk of failure in the field during a module's service life and an appropriate standard test are of urgent importance. The determination of appropriate test procedures and conditions reveals to be most challenging as the PID stress a module is subjected to in a field environment during its lifetime is rather complex. This is due to the fact that PID-stress is highly dependent on the environmental conditions like e.g. humidity [4] and temperature [1][5]. Furthermore modules regenerate from PID at dry and sunny conditions [1][6]. Previously, the temperature dependent R_{sh}-progression during shunting and regeneration was measured [3][7]. Based on these data a preliminary model was developed in order to estimate the actual PID stress of a fielded module and thus evaluate the risk of PID-s occurrence as well as to help finding appropriate test procedures for PID [7].

In this work the PID-s model is presented in more detail and its results are compared to outdoor measurements for validation.

2 EXPERIMENTAL

2.1 Laboratory setup

In order to investigate the PID-s kinetics, mini modules consisting of single p-type solar cells, specially engineered to be prone to PID-s, were produced. These modules were PI-shunted in an environmental chamber at different temperatures. The front glass of the single-cell module was covered with grounded aluminum foil and a high negative potential (-1 kV) was applied to the solar cell. Figure 1 shows the schematic of the experimental setup. To monitor PID-s progression, the solar cell was biased with a voltage in reverse direction V_{rd} (< 0.3 V) at regular time intervals and the current $I(V_{rd})$ was measured. The slope of the *I-V* curve at $V_{rd} = 0$ V could be approximately determined from this assuming $I(0V) = 0$. Note that the assumption is only valid without illumination which was the case inside the chamber. This allowed for in-situ determination of the shunt resistance R_{sh} of the solar cell. It was shown earlier that R_{sh} is an appropriate value to monitor the PID-s progression of this kind of samples [3][7]. A detailed description of the experimental setup is given elsewhere [3]. In addition to the shunting behavior also the regeneration behavior was investigated at different temperatures by setting the voltage bias of previously shunted samples to zero.

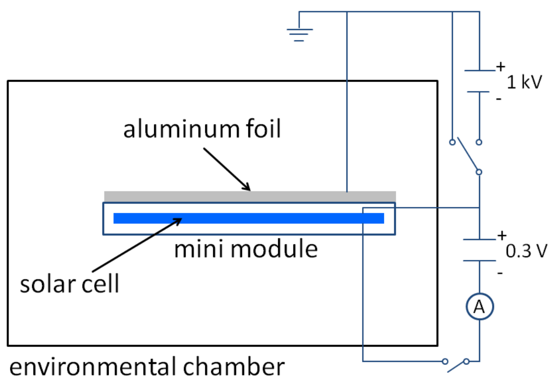

Figure 1: Schematic of laboratory setup

2.2 Outdoor setup

In order to validate the PID-s model presented in this study, outdoor tests using mini modules were performed. The mini modules consisted of single p-type solar cells prone to PID-s like in the laboratory tests. In addition a grounded frame was added and the modules were mounted at an angle of 30° to achieve realistic field conditions with respect to front glass contacting by rain and/or high air humidity. In Fig. 2 an image of the experimental setup is shown. During the day a high negative potential (-1 kV) was applied to the cells incorporated in the modules. This mimics the potential which is generated by the series connected modules in a real PV system and thereby enables PID-s. At nighttime the voltage bias is turned off. A clock timer is used to switch the voltage bias. Note that with this setup precise synchronization of the start and stop of the voltage bias with sunrise and sunset is difficult. In order to account for this, the simulation considers the start/stop of the clock timer instead of irradiation level determined day-night assignment for classification of the time steps, cp. sect. 3.2. The PID-s kinetics is monitored by periodically measuring R_{sh} similar to the laboratory setup shown in Fig. 1. Since this simple setup is only capable to determine the R_{sh} value without illumination, the periodical measurement is only performed at night. During the time of field exposure meteorological data are collected as input for a corresponding simulation.

Figure 2: Picture of outdoor test setup

3 MODELLING PID-s

The general process used to model PID-s is illustrated in Fig. 3. A brief description of the different modeling steps is given in the following.

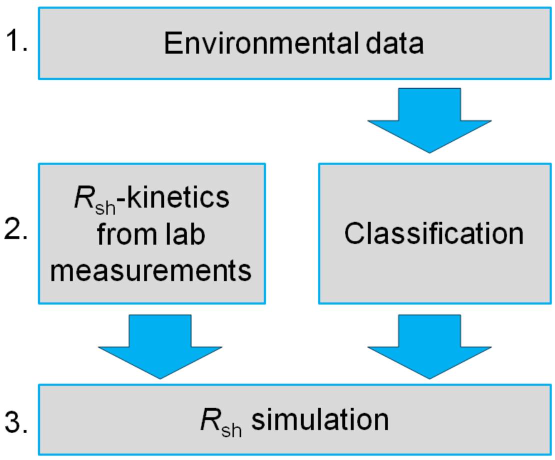

Figure 3: Illustration of the PID-s model procedure

3.1 Environmental data

Environmental data for the installation site during time of interest have to be obtained. The developed model considers module temperature T_{mod}, relative humidity in the vicinity of the module RH_{mod} and rain events. The module specific data are not directly measured but derived from meteorological data. T_{mod} was calculated from the measurements of solar irradiation on module plane IR_{mod}, and air temperature T_{amb} utilizing the nominal operating cell temperature NOCT [8].

$$T_{\mathrm{mod}} = T_{amb} + \frac{(NOCT - 20°C)\cdot IR_{\mathrm{mod}}}{800Wm^{-2}} \tag{1}$$

The typical value of NOCT for Hanwha Q CELLS modules of 45°C was used in this study. RH_{mod} was computed according to the so called Magnus formula [9] using T_{amb}, T_{mod} and the measured relative humidity RH_{amb}.

$$RH_{\mathrm{mod}} = RH_{amb}\cdot e^{\left(\frac{17.62\cdot T_{amb}}{243.12°C+T_{amb}}\right)-\left(\frac{17.62\cdot T_{\mathrm{mod}}}{243.12°C+T_{\mathrm{mod}}}\right)} \tag{2}$$

3.2 R_{sh} kinetics and classification

Key to a PID-s model is the determination of the R_{sh} kinetics in laboratory experiments. Figure 4 shows a complete R_{sh} progression measurement of a mini module obtained at a fixed temperature as an example. The progression was separated into three distinct phases: shunting (S), transition (T) and regeneration (R). Details regarding the R_{sh} kinetics and its analysis can be found in literature [3][7]. Note that in contrast to prior publications the time axis is shown on a logarithmic scale to facilitate better illustration.

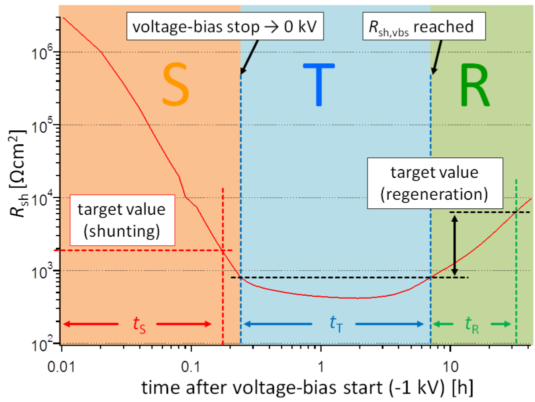

Figure 4: R_{sh} measurement over time of a mini-module during and after PID-s at a fixed temperature. The progression is divided into shunting (S)-, transition (T)- and regeneration (R)-phase

The environmental data (sect. 3.1) were used to assign every individual time step of the simulation to one of the three phases S, T or R. In Fig. 5 the assignment process is illustrated. A time step was assigned to the S-phase if the bias voltage was on and if RH_{mod} was larger than 85% [4] or a rain event was detected. Note, that for a real PV system a non-vanishing solar irradiation on module plane (IR_{mod} > 0) has to be used instead of the bias-voltage -on indicator. If these conditions are not met, the shunting process is considered to be stopped and the time step is assigned to either T-phase or R-phase. For a time step to be assigned to the T-phase the cell type has to show a T-phase at the present R_{sh} value [7], the former time step had to be assigned to an S- or T-phase and in case of T-phase the start of the T phase is not longer ago than the duration of the T-Phase.

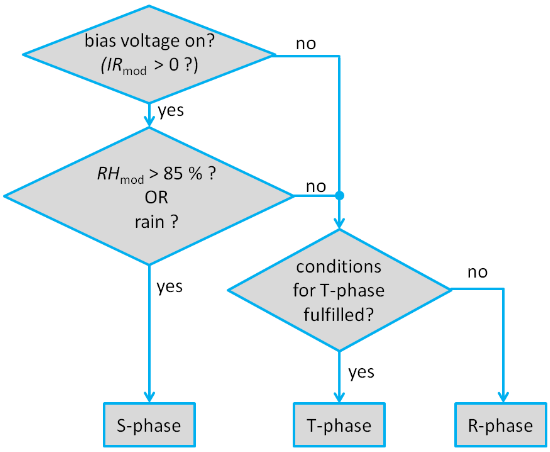

Figure 5: Illustration of phase-assignment process for every time step of the simulation

3.3 R_{sh} simulation

To describe the R_{sh} progression during the S-, T-, and R-phases, respectively, the following empirical formulas dependent on time t were used. Simple exponential functions were chosen for the S- and R-phases,

$$\text{S-phase:} \quad R_{sh}(t) = a_S \cdot e^{\frac{-t}{b_S(T_{mod})}} \tag{3}$$

$$\text{R-phase:} \quad R_{sh}(t) = c_R + a_R \cdot e^{\frac{t}{b_R(T_{mod})}} \tag{4}$$

while the T-phase was described with a polynomial:

$$\text{T-phase:} \quad R_{sh}(t) = a_T(T_{mod}) \cdot (t + b_T(T_{mod}))^2 + c_T \tag{5}$$

a_S, a_R, $a_T(T_{mod})$, $b_S(T_{mod})$, $b_R(T_{mod})$, $b_T(T_{mod})$, c_R, and c_T are constants that have to be determined for the specific module type. Some of them are T_{mod} dependent as indicated. The constants were determined by measuring the times t_S, t_T, and t_R for reaching certain target values as shown in Fig. 4. Details are described elsewhere [3][7].

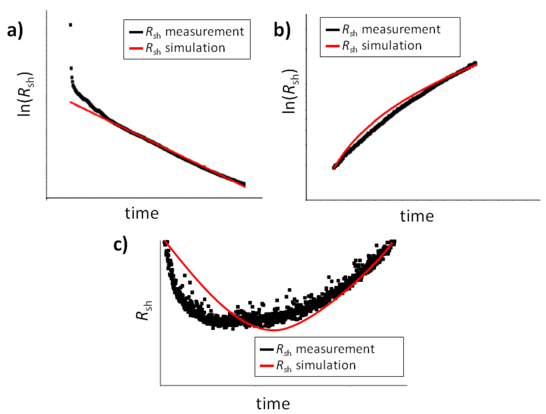

Figure 6: R_{sh} measurements during shunting (a), regeneration (b) and transition (c) compared to corresponding simulations.

In Fig. 6 the corresponding expressions (3)-(5) are shown together with the experimental data for an example in order to enlighten the accuracy of the model. There are differences between measurement and simulation due to the simple formulas. But important features like time constants are represented quite well.

Finally the R_{sh} progression was computed for each time step using the experimentally determined parameters of the R_{sh} kinetics, the module temperature, and the classification of this time step. The classification allows the selection of one of the expressions (3)-(5) which is then used to calculate the R_{sh} -progression considering T_{mod} of this step.

4 RESULTS AND DISCUSSION

4.1 R_{sh} kinetics of two different cell types

It was shown previously that the temperature dependences of the time constants of the three phases are Arrhenius-like [3][7]. In Fig. 7 Arrhenius plots of b_S, b_T, and b_R–which are the time-constants of the different phases–are shown that were determined for two different cell types (A, B). Cell-type B was designed to be highly prone to PID-s, while cell-type A was produced with a higher PID-s resistance. Note that for every temperature several mini modules were investigated. In Fig. 7 the measured data (open symbols), mean values (solid symbols) and Arrhenius fits to the mean values of b_S, b_T, and b_R (dashed lines) are shown.

It was found that for cell-type B b_S is generally lower compared to cell type A confirming its higher PID-s resistance. In contrast to this, b_R of cell-type B shows higher values compared to cell-type A indicating a faster regeneration progress of cell-type A. In case of b_T, cell-type B again shows higher values which means that in addition to the slower regeneration cell-type B also shows a longer T-phase compared to cell-type A.

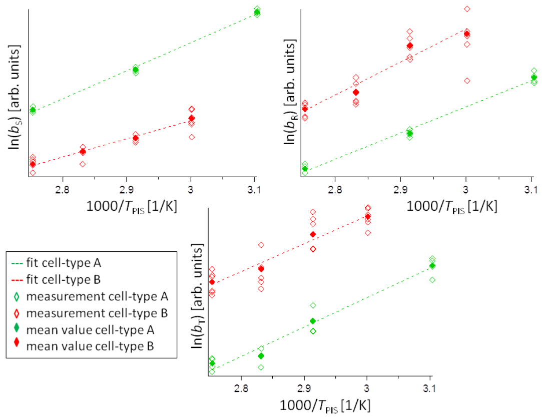

Figure 7: Arrhenius-plots of b_S, b_T and b_R for mini modules with two different cell types. The measured data (open symbols), mean values (solid symbols) and Arrhenius fits (dashed lines) are shown.

4.2 Comparison to outdoor measurements

In order to validate and improve the PID-s model the R_{sh} progression of mini-modules fielded in Thalheim (Germany) was measured and compared to simulation results. Four mini-modules were investigated, two consisting of highly PID-s prone cell-type B (sample 3, 4) and two consisting of more PID-s resistant cell-type A (sample 1, 2), respectively. The measured night-time R_{sh} progression is shown in Fig. 8 together with simulation results employing meteorological data collected during the time of field exposure.

First it can be noted that the four mini-modules show different initial shunt resistance values. While for both mini-modules with cell-type B R_{sh} is about 700 kΩcm^2 the mini-modules with cell-type A show an intrinsic R_{sh} of 1000 kΩcm^2 and 200 kΩcm^2, respectively. This is due to variations in the cell production and does not affect the R_{sh} kinetics caused by PID-s. Further it can be noted that the measured R_{sh}value is temperature dependent and the degree of temperature dependence can vary significantly between different samples [3]. Due to this sample 2 shows only small changes of R_{sh} while sample 1 exhibits considerable fluctuations. Comparison of the temperature during measurement (i.e. at night time) with the R_{sh} value of sample 1 revealed a clear correlation. Also small fluctuations of the R_{sh} values of samples 3 and 4 can be attributed to temperature-changes. But the overall R_{sh} progression is clearly affected by PID-s.

After 900 hours of field exposure with daytime voltage bias of -1 kV the mini-modules with cell-type A (samples 1 and 2) show only small changes of the R_{sh} value. In contrast to this, samples 3 and 4, which incorporate cell-type B, show a significant decrease of R_{sh} down to values below 2 kΩcm^2 indicating a cell-performance loss [3].

The solid lines in Fig. 8 show the simulation results for cell type A (green) and B (red), respectively. The initial R_{sh} was set to 650 kΩcm^2. Comparison between measurements and model calculations show good qualitative agreement. As predicted by the calculation for cell-type A the PID-stress during field exposure is not large enough to affect the R_{sh}-value of samples 1 and 2 significantly. For highly PID-s prone cell-type B the calculation predicts a fast decrease of R_{sh} in good agreement with the decrease observed for samples 3 and 4 in the experiment.

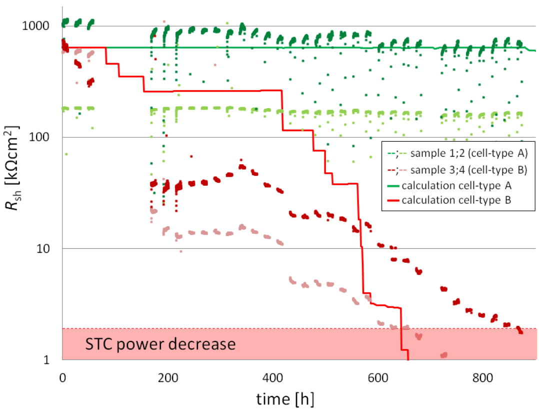

Figure 8: Night-time measurement of R_{sh} over time of fielded mini-modules (dashed lines) together with R_{sh} model calculations (solid lines).

Nevertheless there are differences between model results and experimental data of the R_{sh}-progression concerning cell-type B. These might be explained by a combination of different factors:

(a) Classification of the meteorological data affects the calculated results. In the calculation presented in Fig. 8 hourly data-sets were employed as only these are commonly available. Consequently PID-s events can never be shorter than one hour leading to an overestimation in case of short rain or dew events. In addition use of hourly solar irradiation values can lead to differences between the calculated and real module-temperature, which affects the prediction of dew formation events of the PID-s model and thus PID-s stress duration. In addition this temperature difference in combination with the nonlinear temperature dependence of R_{sh} progression leads to deviations. For the Thalheim (Germany) test site data is available in one minute intervals and a quantification of the influence of the discretization is currently under way.

(b) In addition also a systematic overestimation of meteorological events (e.g. rain) on the contacting of the module surface is possible. A detailed analysis of the meteorological data can help to judge the influence of this effect and is also currently ongoing.

(c) As described in section 3.3 simple empiric functions are used to calculate the R_{sh} progression. It was found that for extended R_{sh} decrease this simple estimation can lead to an overestimation of the shunting.

(d) Additional factors not considered in the current model can have an influence on the R_{sh}-progression. For example, indications can be found in literature that cells exposed to solar irradiation during PID-s show a slowdown of the R_{sh} decrease [10]. Also a history dependence of the shunting behavior was reported altering the R_{sh} behavior [11].

5 CONCLUSION AND OUTLOOK

A model was developed in order to predict the time of PID-s onset in field installations at a specific location based on laboratory characterization of PID-s kinetics and local meteorological data. First outdoor experiments show good qualitative agreement between model and experiment. Deviations between model results and experimental data can be attributed to model approximations and limitations of meteorological data used. A detailed analysis of these deviations and a comparison with calculations employing one minute interval meteorological data is ongoing in order to improve model and prediction accuracy. After complete validation, this model will make it possible to evaluate the risk of PID-s onset during the functional life time of a module in a specific installation site. This will also prove valuable in defining appropriate stress levels for laboratory PID tests.

6 ACKNOWLEDGEMENT

This work was partly supported within the Spitzencluster Solarvalley project xμ-Clip (FKZ 03SF0452) by the German Federal Ministry of Research and Technology.

7 REFERENCES

[1] S. Pingel et al., "Potential Induced Degradation of solar cells and panels", Proceedings of the 35th IEEE Photovoltaic Specialists Conference, Hawaii, 2011

[2] M. Schütze et al., "Laboratory study of potential induced degradation of silicon photovoltaic

modules", Proceedings of the 37th IEEE Photovoltaic Specialists Conference, Seattle, Washington, USA, 2011, pp. 821-826

[3] C. Taubitz et al., "Towards a kinetic model of potential-induced shunting", Proceedings of the 27th European PV Solar Energy Conference, Frankfurt, Germany, 2012, pp. 3172-3176

[4] M. Schütze et al., "Investigation of potential induced degradation of silicon photovoltaic modules", Proceedings of the 26th European PV Solar Energy Conference, Hamburg, Germany, 2011

[5] J. Berghold et al., "Potential Induced Degradation of solar cells and panels", Proceedings of the 25th European PV Solar Energy Conference, Valencia, Spain, 2010, pp. 3753-3759

[6] P. Hacke et al., "System voltage potential-induced degradation mechanisms in PV modules and methods for test", Proceedings of the 37th IEEE Photovoltaic Specialists Conference, Seattle, Washington, USA, 2011.

[7] C. Taubitz et al., "Kinetic description and modeling of potential induced degradation", Proceedings of the 28th European PV Solar Energy Conference, Paris, France, 2013, pp. 3321-3323

[8] J.Wohlgemut, J. Posbic, J. Anderson: "Energy ratings for pv modules", Proc.14th European Photovoltaic Solar Energy Conference, Barcelona, Spain, 1997.

[9] D. Sonntag, „Important new Values of the Physical Constants of 1986, Vapour Pressure Formulations based on ITS-90, and Psychrometer Formulae", Z. Meteorol. 40, 1990, 340-344

[10] S. Koch et al., "Work towards simulation model for the potential induced degradation effect on crystalline silicon cells", Proceedings of the 28th European PV Solar Energy Conference, Paris, France, 2013

[11] P. Hacke et al., "System voltage potential-induced degradation mechanisms in PV modules and methods for test", Proceedings of the 37th IEEE Photovoltaic Specialists Conference, Seattle, Washington, USA, 2011