Potential induced degradation (PID): a test campaign at module level

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Abstract – Potential induced degradation (PID) of photovoltaic (PV) modules gets a lot of attention since 2010 when Solon published their findings about a degradation mechanism in their PV modules caused by high potential differences. [1] When multiple PV modules are connected in series, a potential difference up to 1000 V or at some places even 1500 V is created between the cell and the grounded frame. This electrical field causes a leakage current and ion diffusion. PID is a multi-level degradation with causes and solutions at cell, module and system level.

A test campaign was conducted within the frame of a feasibility study for pidbull, a curing technology for PID developed by pidbull nv. 80 PV modules were characterized whereof 49 PV modules were stressed and cured for PID. The selected set of PV modules was composed of 49 different module types of 33 brands. The test was done according to the foil-method, as described by the standard in progress IEC 62804. However, to apply higher stressing and curing rates, the modules were tested with an aluminium foil inside a climate chamber for 96 hours.

After the stress test, only 22 % of the tested modules passed the 5 % loss criteria as described by IEC 62804. In other words, 78 % out of a set of todays most installed PV modules in Flanders are PID sensitive. Remarkable is that only 16 out of the 49 PV modules have less than 20 %PID after the stress test. Additionally, a linear trend for PID reversibility was shown for modules with a stress level of less than 85 %. The modules which lost more than 85 % due to PID showed a lower recovery rate or in worst case didn't recover at all.

1 Introduction

The Edison Energy group is an asset management company that manages around 33.000 kWp of installed PV modules in Flanders. Many publications about PID have emerged since 2010 when a company called Solon published their findings about a degradation mechanism in their PV modules caused by high potential differences. [1] Solutions to the problem for new PV modules as well as cures for affected PV modules have been published.[1]–[4]

This inspired the Edison Energy group to develop pidbull, a PID curing technology. This test campaign was conducted within the frame of a feasibility study for pidbull. 80 PV modules installed in the past 10 years were characterized whereof 49 PV modules were subjected to a stressing and a curing test for PID according to the standard in progress IEC 60804-1: *"test methods for detection of potential-induced degradation of crystalline silicon photovoltaic (PV) modules"*. Others already conducted a similar test. In these tests, a slightly different test protocol was used. This report focusses mainly on PV modules as installed in Flanders, probably resulting in a different set of PV modules to be tested. [3][5][6]

In this report the physical degradation process of PID will be described first, followed by the materials and methods as used in this experiment. Next, the experimental results are presented followed by a discussion and conclusion.

2 Potential induced degradation

2.1 Physical degradation process

PID has been described as early as 2005 as the surface polarization effect by Swanson *et al.* [4] They described the degradation of Sunpower cells by high voltage stress (HVS) which is caused by a surface charge that is formed near the passivated front surface of a high efficiency back contacted n-type silicon cell as shown in Figure 1. In this case the degradation effect was very significant already at module voltages of +160 V. In this publication they already showed that this surface polarization effect can be found also in standard contacted cells. This effect was also shown to be reversible by applying a reverse bias and also by UV irradiation, which can remove the trapped surface charge.

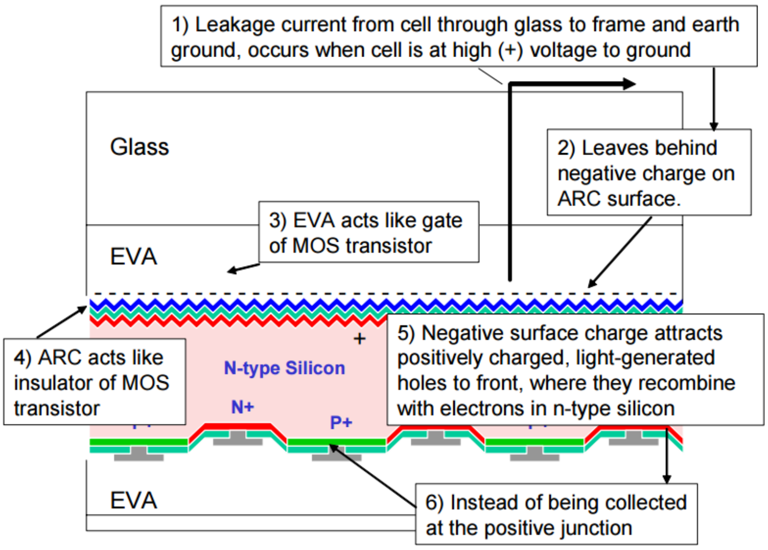

Figure 1: Cross-section of a back-contact solar cell with n-type passivation capped with a silicon dioxide, silicon nitride ARC. [4]

In the paper by Pingel *et al.* [1] a similar degradation caused by HVS was described on p-type standard cells. Besides the precondition of having a PID sensitive cell they also showed ways to stop or minimize PID on panel and system level. According to them, PID depends on polarity and the level of the potential between the cell and ground. On panel level they describe the leakage currents in a lab PID setup as shown in Figure 2. As was already described, they also mention the possibility to recover the lost power by applying reverse potentials as shown in Figure 3.

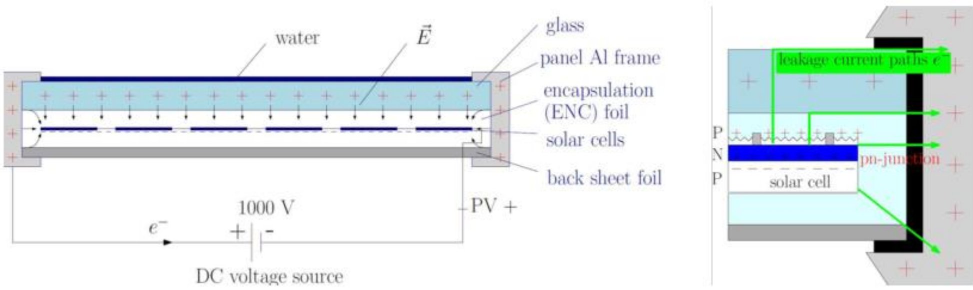

Figure 2: PID test setup and leakage currents as described by Pingel et al. [1]

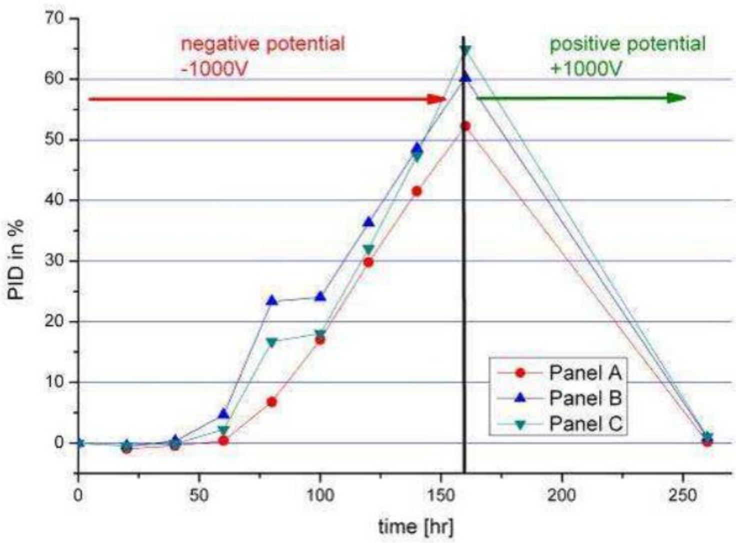

Figure 3: PID and recovery by reverse potential. [1]

The mechanism behind PID on these p-type cells was further investigated by Bauer *et al.* [7] PID occurs on panel level when the combination of soda lime glass, EVA encapsulant and the anti-reflective coating (ARC) on the cell promote PID. Sodium ions (Na+) in the soda lime glass combined with leakage current pathways. Secondary ion mass spectroscopy (SIMS) studies have shown high Na+ concentrations in the anti-reflective coating (ARC) caused by the leakage currents under HVS. Tests using other sorts of glass also showed PID caused by other ions in glass. According to Bauer these ions cause the shunt paths lowering the shunt resistivity of the cell.

More recent studies of the root cause of PID of the shunting type have looked deeper into how Na causes this shunting behaviour. [8]–[10] They found out that Na will stick in stacking faults in the Si lattice and thus causes a direct shunt path across the p-n junction.

2.2 Experiences on PID testing

Dietrich *et al.* reported on PID testing in 2012. [3] They conducted PID tests on 95 PV modules in different test conditions. The foil-method, which is schematically shown in Figure 4, was used to stress test 77 PV modules. This was done at 50 °C and 50 %RH for 48 hours. 11 PV modules were tested without the foil at a temperature of 60 °C and a relative humidity of 85 %. The remaining 7 modules were tested with the foil-method at 50 °C and 50 %RH for 168 hours. 46 % of the tested PV modules failed the 5 % loss criteria as stated by IEC 62804. They also described a scattered loss of power per module type of the same manufacturer.

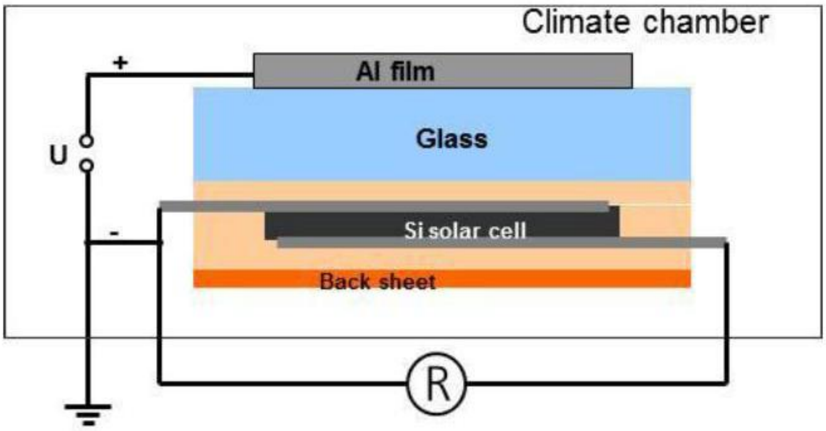

Figure 4: A simplified representation of the foil-method according to IEC 62804. [3]

Koch *et al.* [11] reported on the voltage dependence of PID in modules with crystalline silicon cells. This study concludes that the susceptibility of PID varies significantly over a wide range of modules. Some modules show a major loss in performance; <10 % of P_{nom} after <60 hours of stressing with a voltage of 100 V whereas some modules don't show any power loss after 900 hours of stressing at 1500 V. This indicates that small PV installations (such as household PV systems) as well as big PV installations (such as PV farms) can be affected by PID or not.

Another study of Koch *et al.* [12] showed an irreversible behaviour of PID for PV modules with a power loss of 85 % or more. According to Koch, PV modules with a degradation of more than 85 % were only recoverable for, on average, 59 % whereas PV modules with a degradation of less than 85 % were recoverable for, on average, 97 %.

Mostly, degradations of module efficiencies due to HVS, such as PID, are reversible. However, irreversible forms of PID caused by electrochemical reactions, resulting in electro-corrosion and/or film delamination in the modules, have been reported. This form of irreversible PID affects primarily thin film technologies, which are not widely used in PV installations today. [13][14]

3 Materials and methods

3.1 Standard for PID testing: IEC 62804

IEC 60804-1: *"test methods for detection of potential-induced degradation of crystalline silicon photovoltaic (PV) modules"* is a standard in progress which describes two different test methods to stress PV modules for PID. The first method described in this standard has to be conducted inside a climate chamber at 60 °C ± 2 °C and 85 %RH ± 3 %RH. The maximum system voltage has to be applied for 96 hours between the cells and the frame, which is grounded in the field. The second method proposed by the standard can be conducted at room temperature (25 °C ± 1 °C) with a relative humidity less than 60 %. The maximum system voltage has to be applied for 168 hours between the cells and an aluminium foil, which covers the front side of the module. For faster and further degradation, this method can be combined with higher temperatures. However, after stressing the PV module, the total degradation with both methods has to be less than 5 % to pass the test.

3.2 Stress test

In order to apply a higher stress level to the modules, the proposed tests were combined; the modules were covered with an aluminium foil and stressed for 96 hours inside a climate chamber (a CTS, CW-40/19) at 60 °C ± 2°C and 60 %RH ± 5 %RH. This setup is shown in Figure 5. A voltage difference of 1000 V between the cells, from which the negative and the positive output were short circuited, and an aluminium foil was provided by an Ultravoltage BT-GP-1P30 voltage source. Figure 6 shows the aluminium foil covering the front surface of the modules.

Figure 5: The climate chamber with the PV modules stacked for the PID stress test.

Figure 6: Some of the PV modules prepared with an aluminium foil

3.3 Recovery test

The recovery of the modules was carried out with the same setup and the same duration. However, the voltage was applied by 4 in parallel-connected pidbulls, a PID recovery device developed by pidbull nv, part of the Edison Energy group. Note that pidbull is designed for recovering modules in the field and therefore has a voltage difference of 1000 V at its nominal operating point. However, since an aluminium foil was used in this setup a larger leakage current will flow in comparison with an experiment test where only the frame is connected. This results in a slightly lower output voltage due to resistance losses (± 950 V).

3.4 Characterization of the modules

A mobile lab of Solartester BV carried out the characterization of the modules. A flash test and EL-image of the modules were obtained before the stress test, after the stress test and after the recovery period. Note that the outcome of an IV curve is a quantitative representation of PID, while an EL-image is only a qualitative representation for PID. The process of characterization, stressing and recovering the modules for PID is presented in Figure 7.

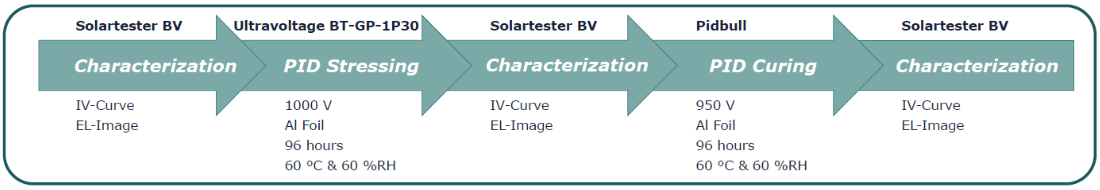

Figure 7: A flowchart which represents the working method to characterize, stress and recover the modules for PID.

3.5 Panel selection

A wide variety of PV module brands and/or types was selected from partners, potential clients and managed PV-parks of the Edison Energy group. As displayed in Figure 8, the most negative (PV-) and the most positive (PV+) panel of 31 strings were selected and subjected to an initialization test. After the initialization test, the panels from the positive side of the string were subjected to a stress test and a recovery cycle. All PV modules in this set have been installed within the past 10 years. An additional set of 18 brand new PV modules was subjected to the initialization test, stress tests and recovery cycle as well. A total of 49 different PV module types of 33 brands were tested, resulting in 80 PV panels to be tested. The 49 different module types cover a large part of the list of most-installed PV modules today in Flanders.

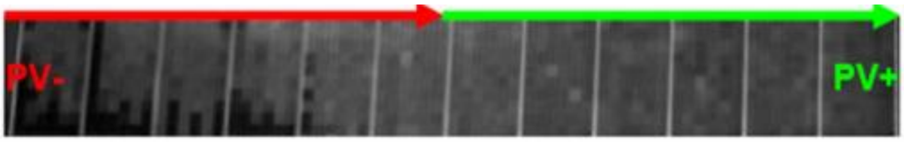

Figure 8: EL-image of a string of PV modules with the most negative (PV-) panel at the left side and the most positive (PV+) panel at the right side. [1]

4 Experimental results

4.1 Quantifying PID

In what follows, the degradation caused by PID is presented by $\%PID_S$ and is calculated as follows:

$$\%\mathrm{PID_S}\ [\%] = 1 - \frac{\mathrm{P_S}}{\mathrm{P_I}}$$

with P_S [W] the maximal power output of the PV module after stressing and P_I [W] the initial maximal power output of the PV module before the stress test.

The degradation due to PID which is still present in the PV modules after the curing cycle is presented by $\%PID_C$ and is calculated as follows:

$$\%\mathrm{PID_C}\ [\%] = 1 - \frac{\mathrm{P_C}}{\mathrm{P_I}}$$

with P_C [W] the maximal power output of the PV module after curing.

The recovered %PID is presented by $\%PID_R$ and is calculated as follows:

$$\%\mathrm{PID_R}[\%] = \frac{\mathrm{P_C}\text{-}\mathrm{P_S}}{\mathrm{P_I}}$$

After the stress test, the PV modules were assigned a number. The PV module with the lowest $\%PID_S$ was assigned with number 1 whereas the PV module with the highest $\%PID_S$ was assigned with number 49. This numbering will be used throughout the rest of this report.

4.2 Stress test

After stress testing the PV modules for PID during 96 hours at the previously mentioned conditions, only 22 % passed the 5 % loss criteria, as stated by IEC 62804. Note that the stress level applied to these panels exceeds the stress level proposed by the standard in progress. Figure 9 displays the $\%PID_S$ of the 49 PV modules subjected to the stress test together with the 5 % limit to pass the PID test.

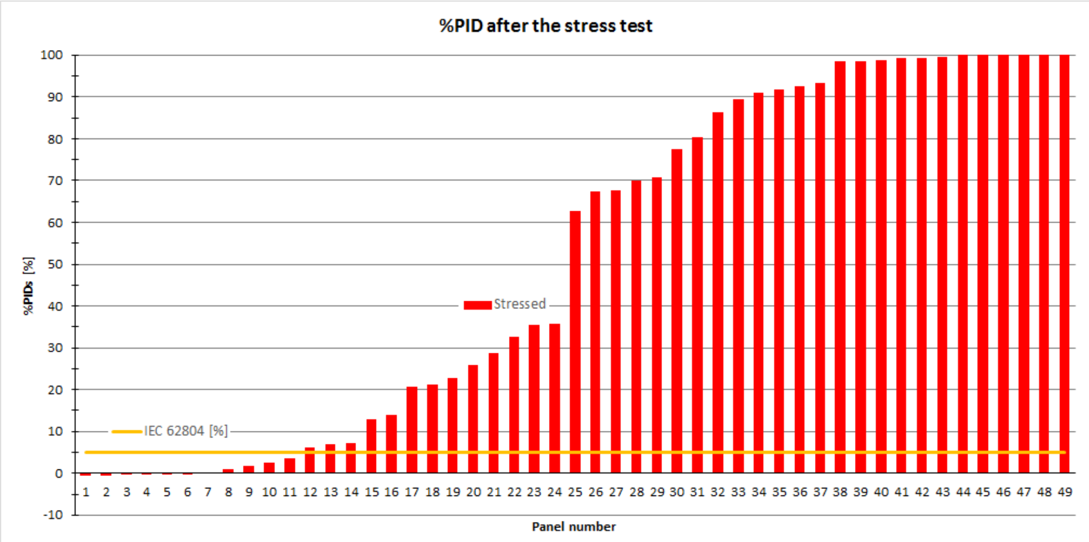

Figure 9: The %PID$_S$ of the 49 PV modules after stressing as well as the 5 % loss criteria according to the IEC 62804 standard.

The distribution of stressed PV modules in function of %PID$_S$ is shown in Figure 10. This histogram shows that 19 out of 49 stressed PV modules are degraded more than 80 % by PID. Only 16 out of 49 modules have a %PID$_S$ of less than 20 % after the stress test. Note that the %PID$_S$ for a few PV modules had a negative value. However, since these values were very small (<1 %), it can be stated these results were obtained due to measurement errors.

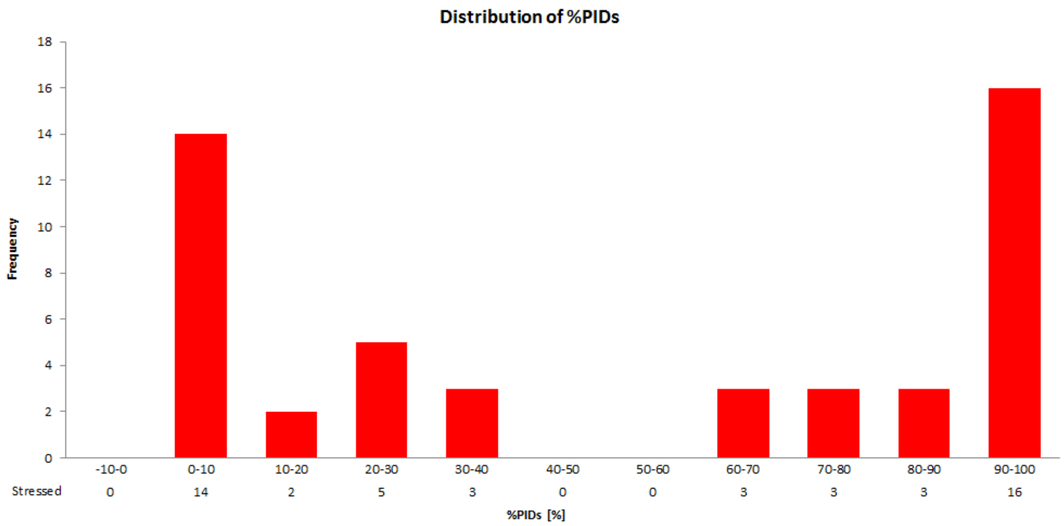

Figure 10: The distribution of stressed PV modules in function of %PID$_S$.

4.3 Recovery test

After recovering the PV modules with pidbull for 96 hours at previously mentioned conditions, 37 % of the PV modules passed the 5 % loss criteria, representing an increase of 15 %. As previously mentioned, the voltage of the curing cycle was about 50 V lower than the stress cycle. The %PID$_C$ after recovery is shown in Figure 11 together with the 5 % limit to pass the PID test.

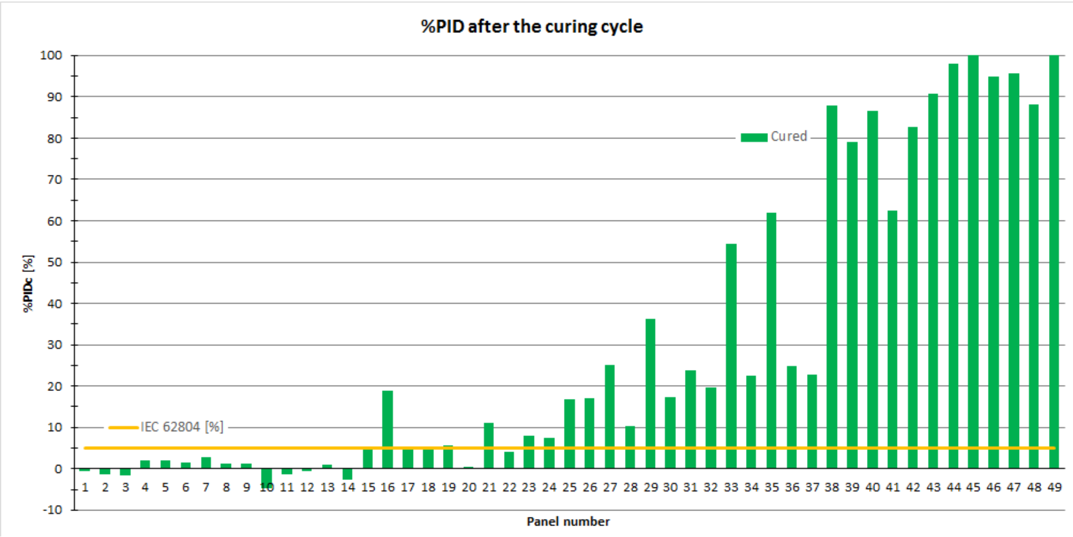

Figure 11: The %PID$_C$ of the 49 PV modules after curing as well as the 5 % loss criteria according to the IEC 62804 standard.

The distribution of cured PV modules in function of %PID$_C$ is shown in Figure 12. This histogram shows that only 10 out of 49 modules still have a %PID$_C$ level of more than 80 % (in comparison to 19 out 49 modules after the stress test). Furthermore, 29 out of 49 stressed PV modules are cured to a %PID$_C$ of less than 80 % (in comparison to 16 out of 49 after the stress test). Apart from measurement errors, two modules tend to be recovered more than they were stressed. An overall recovery by pidbull is shown clearly.

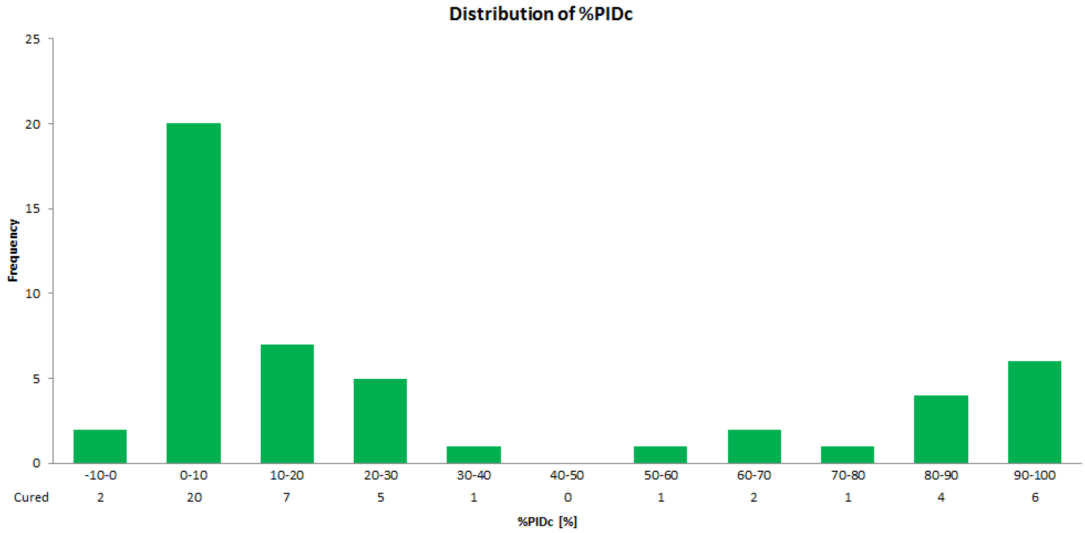

Figure 12: The distribution of cured PV modules in function of %PID$_C$.

4.4 Reversibility of PID

When %PID$_R$ is plotted in function of %PID$_S$, as shown in Figure 13, two different degradation mechanisms can be distinguished. An overall linear trend can be seen with a %PID$_S$ of less than 85 % (blue points). However, some modules with a %PID$_S$ of more than 85 % (red points) seem to recover slower or, in worst case, don't recover at all. This phenomenon is already mentioned by Koch *et al.* [12] Further research has to be conducted to look into the mechanism which causes this irreversible form of PID at higher %PID$_S$. The modules which are located at the left side of the bisector (grey line) tend to be recovered more than they were stressed. Note that no intermediate measurements were conducted during recovery.

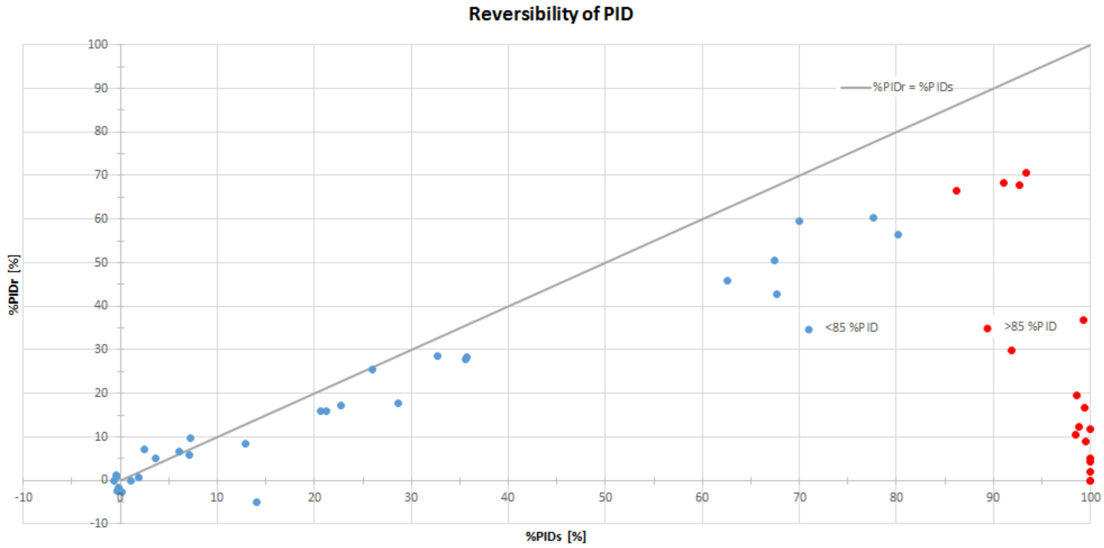

Figure 13: The reversibility of PID. Two different degradation mechanisms can be distinguished, clarified with blue and red data points.

The normalized IV curves of one PV module after every test are shown in Figure 14. The black line in this graph shows the IV curve of the module after the initialization test. The red line shows the IV curve after the stress test. At this point, the maximum power point of the module was degraded by PID for 93 %. The green line shows the IV curve after the recovery cycle. Pidbull was able to recover the maximum power point of this module and only 22 % of the degradation due to PID was still present after the recovery cycle.

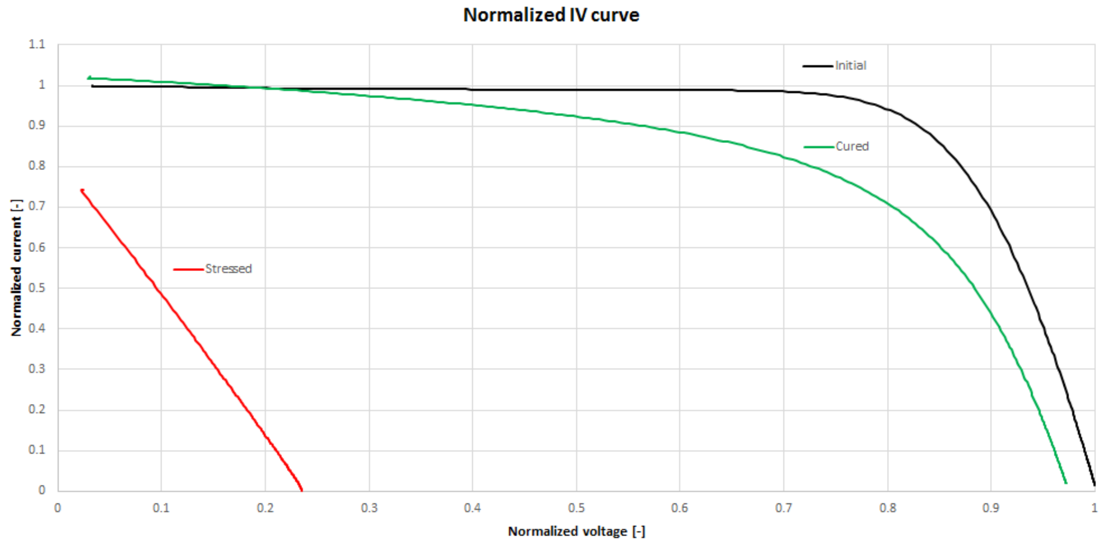

Figure 14: The normalized IV curves of one PV module after the 3 tests. The maximum output power of this module degraded for 93 % due to PID. By connecting it to pidbull, only 22 % of the degradation due to PID was still present.

A plot of $\%PID_r$, averaged over 10 modules, in function of $\%PID_S$ is shown in Figure 15. The horizontal bars represent the range of the $\%PID_S$ of the selected group of PV modules. The vertical bars represent the standard deviation of the $\%PID_C$ of the selected group. For this purpose, the set of 49 PV modules was divided in five groups. Every group represents 9 or 10 modules in the same sequence as used before. The first group (module number 1 – 10) includes degradation ratios ranging from -0.5 to 2.5 $\%PID_S$. The average degradation for this group is <1 %. On average, this group of 10 PV modules was degraded by PID for only 0.2 % after the recovery cycle. The second group covers degradation ratios ranging from 4 to 26 $\%PID_S$ with an average of 14 $\%PID_S$. This set of modules had an average of 3.5 $\%PID_C$ after recovery. The next group covers a range from 29 to 77 $\%PID_S$ with an average of 55 $\%PID_S$. After curing, this group had on average 15 $\%PID_C$ left. The data points of the last two groups include mainly degradation ratios of >85 $\%PID_S$. As already discussed for PID stress levels >85 %, an irreversible degradation is observed. Group 4 covers a range from 80 to 99 $\%PID_S$ with an average value of 92 $\%PID_S$. On average, this group had 48 $\%PID_C$ left after the curing cycle. The last group of (9) PV modules includes $\%PID_S$ values ranging from 99 % to 100 %. On average, this group had 90 $\%PID_C$ left after recovery. This graph highlights the importance of detecting PID in an early stage in order to recover it to an acceptable level.

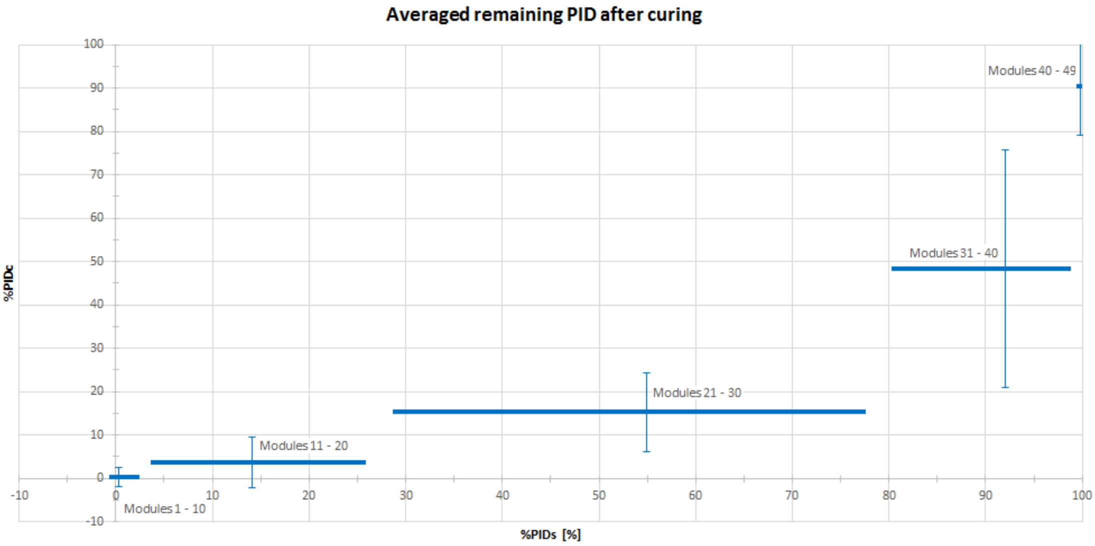

Figure 15: The remaining power after curing ($\%PID_C$), averaged over 10 PV modules, in function of $\%PID_S$. The horizontal bars represent the range of the $\%PID_S$ of the selected group whereas the vertical bars represent the standard deviation.

4.5 Impact on V_{OC}

The degradation of the open circuit voltage after stress testing the PV modules for PID is presented by $\%V_{OCS}$ and is calculated as follows:

$$\%V_{OCS}\ [\%] = 1 - \frac{V_{OCS}}{V_{OCI}}$$

with V_{OCS} the open circuit voltage after the stress test and V_{OCI} the initial open circuit voltage of the PV modules.

When the $\%V_{OCS}$ is plotted in function of the $\%PID_S$, a clear trend can be seen as shown in Figure 16. However, only PV modules with a high degradation level due to PID can be recognized by a degradation in V_{OC}. The V_{OC} doesn't degrade significantly until %PID levels of 40 % or higher are reached. Martínez-Moreno *et al.* [15] reported on the dependency of the V_{OC}. He concluded no significant changes for low $\%PID_S$ as well.

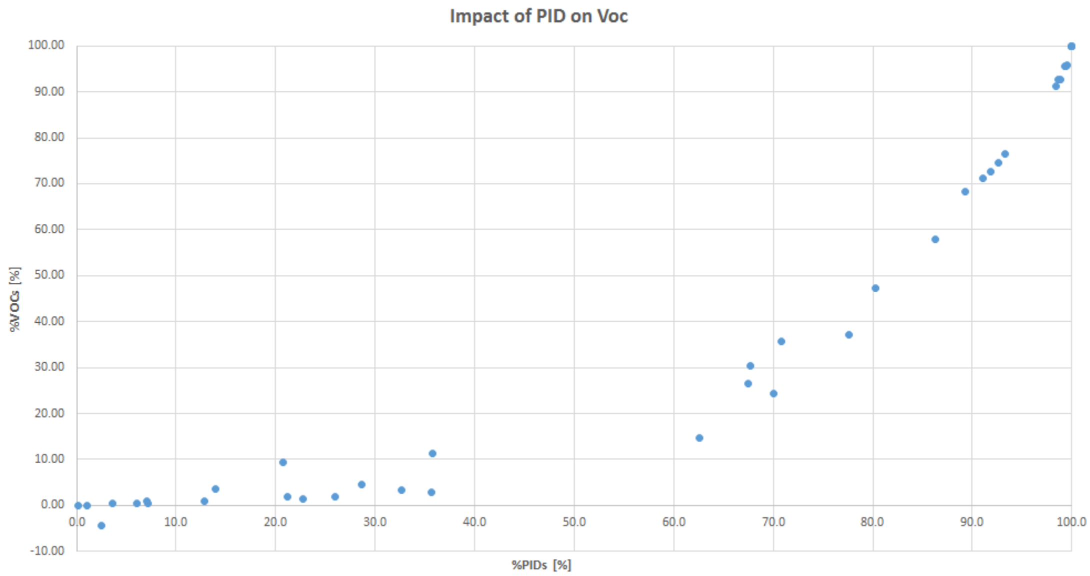

Figure 16: Plot of the %V_{OCS} in function of %PID_S. The V_{OC} only degrades significantly for higher PID levels (40 % or more).

5 Discussion and conclusion

A test campaign on module level for PID was conducted within the frame of a feasibility study for pidbull, a PID curing technology. After the stress test, only 22 % of the tested modules passed the 5 % loss criteria as described by IEC 62804. In other words, 78 % out of a set of todays most installed PV modules in Flanders are PID sensitive. Remarkable is that only 16 out of the 49 PV modules have less than 20 %PID after the stress test. Note that the stress level applied to the modules exceeded the stress level as prescribed by the standard because the foil method was combined with a high temperature. While curing the modules, a slightly lower voltage (+-50 V) was applied in comparison to the stress test. This might result in a lower recovery rate, which means that the modules were not fully recovered after the recovery cycle and this might influence the graph as shown in Figure 13. A steeper trend line is expected for modules with PID levels lower than 85 % when recovering with the same voltage as the stress test or when a longer recovery cycle is applied. However, further research has to be conducted in order to validate last statements. Figure 13 also shows an irreversible form of PID for modules with higher PID levels than 85 %. Preliminary results show that PID causes a decrease in shunt resistance, having an effect on the fill factor in an early stage. When the modules degrade even further, the open circuit voltage will be decreased, followed by a decrease in short circuit current. Further studies will look into the recovery of the fill factor, open circuit voltage and short circuit current and hopefully will give more insight in the irreversible part at high PID levels. It can be concluded that the pidbull technology is able to cure PV modules for PID. However, it is important to detect PID in an early stage in order to be able to recover the PV modules to an acceptable level.

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