Potential-induced degradation (PID) and its correlation with experience in the field

Juliane Berghold, **Simon Koch**, **Anja Böttcher**, **Asier Ukar**, **Mathias Leers** & **Paul Grunow**, Photovoltaik-Institut Berlin (PI-Berlin), Germany

ABSTRACT
Statistical data on potential-induced degradation (PID) testing at the panel level are discussed in terms of their field relevance and the actual occurrence of PID in the field, since the latter is strongly dependent on both the specific climate and the weather conditions at a certain location as well as on the system configuration realized in a specific power plant. The correlation of outdoor conditions and leakage current is also considered with regard to a suitable standard test for solar panels. Real outdoor data are shown for PID-affected power plants. Indoor and outdoor recovery is demonstrated for PID in real solar plants as well as in lab and outdoor set-ups. Apart from 'measuring' PID in suitable tests and in the field, approaches are also presented for the mitigation of PID at the panel and system level.

Introduction
Potential-induced degradation (PID) is a phenomenon which is still attracting increasing attention not only because of its growing importance for obvious technological reasons (higher system voltages and new technologies and materials), but also because of rising awareness throughout the whole PV community, beginning with the first publications on 'standard technology' more than two years ago [1–3]. This awareness is also due to the interest in energy yield optimization by minimizing overall degradation. PID is one degradation mechanism, and its occurrence in the field is not just dependent on the PID sensitivity of the solar panels and on a high potential relative to ground. Because of the variation of panel leakage current with temperature and humidity, a clear correlation can be observed between PID occurrence and weather conditions.

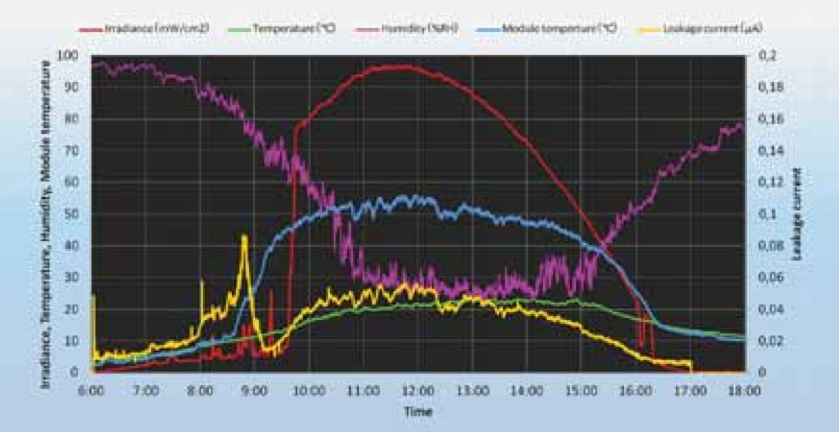

Figure 1. Leakage current data for a sunny day in the field (Yamanashi, Japan) for a panel at –1000V, depending on outdoor conditions (temperature, humidity and irradiance) [4].

> "A clear correlation can be observed between PID occurrence and weather conditions."

Figure 2. Morning dew responsible for the leakage current peak in the morning [4].

Outdoor conditions and test methods
The occurrence and extent of PID strongly depend on outdoor conditions, as they determine the leakage current at the panel level. Fig. 1 shows the leakage current trend as a function of measured outdoor conditions for a sunny day. Two different regimes can be distinguished here: first, the leakage current peak in the morning, which is mainly humidity driven – morning dew as illustrated in Fig. 2; and second, a rather broad bump during the hours around noon, which is obviously mainly temperature driven because of the daily trend of irradiance.

As there are different and varying leakage currents observed not only in one location because of varying parameters, but also from location to location, it has to be stated that the risk of occurrence of PID in the field varies significantly for different

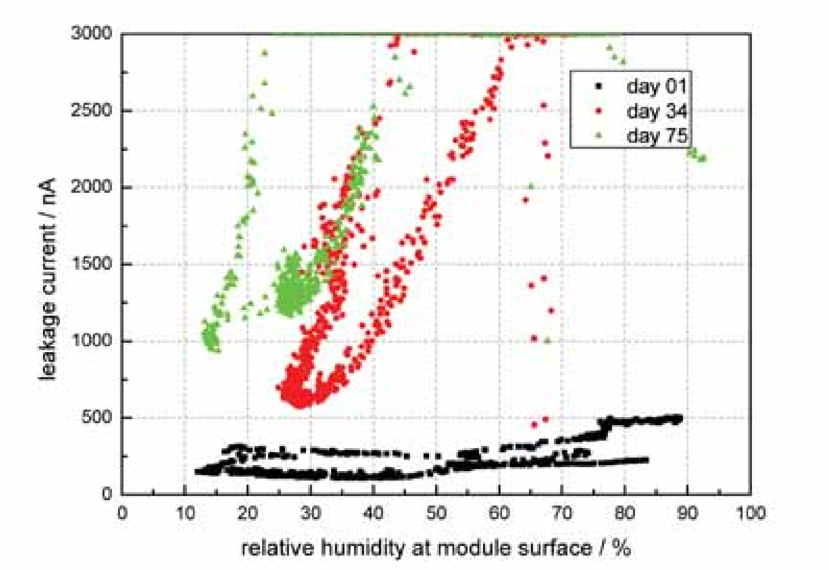

Figure 3. Leakage current data captured on three different days in the Canary Islands for two different panels at –1000V, as a function of relative humidity (RH) [5].

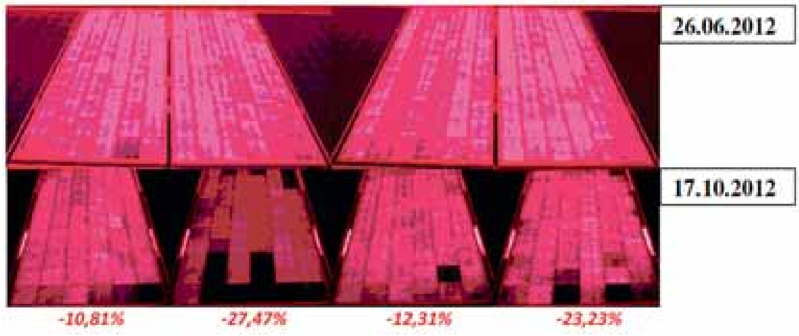

Figure 4. Progressive PID in the field: electroluminescence (EL) images and related power loss for a solar plant in southern Spain (about 30km from the sea).

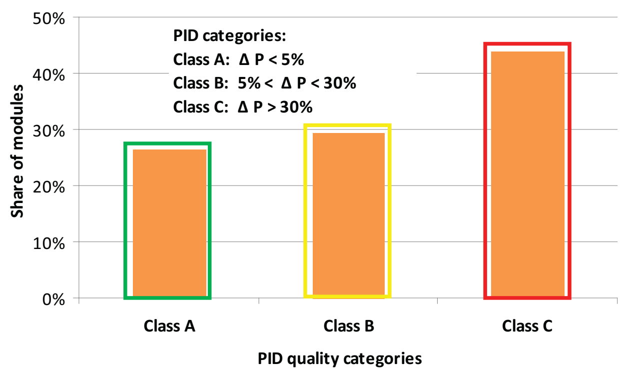

Figure 5. PID test results at PI-Berlin (2012: about 45 different panel types tested).

locations. Leakage current data from ISE Fraunhofer are shown in Fig. 3 for a location with a higher PID risk, the Canary Islands; leakage current data were captured for different panels on three different days. In the beginning, the leakage currents for the different panels were comparatively low, although the maximum values attained were about five times higher than for the lower risk region of Japan presented above (0.1μA vs. 0.5μA). Five weeks later there was a significant increase in detected leakage current, and after ten weeks the observed maximum leakage currents were about five times the initial values and partly beyond the detection limit of 3μA. This could somehow be correlated to an increase in surface conductivity as a result of salt particles and soiling.

These findings tie in quite nicely with the observation that a significant percentage of PID-affected solar plants are situated in rather warm climates and near the coast. Fig. 4 presents an example of a solar plant in southern Spain, where PID was detected after the hottest part of the year.

> "A significant percentage of PID-affected solar plants are situated in rather warm climates and near the coast."

With this in mind, the target of a suitable test method for PID and an upcoming standard test should be the simulation and the acceleration of real voltage-induced ageing and degradation in the field. There are an increasing number of test methods in place, but unfortunately they vary mainly in the specific test conditions for temperature, humidity and contact scheme. They all have one thing in common: they lack real outdoor correlation data. The most relevant test conditions are:

- Biased damp heat (DH): 60°C/85% RH, –1000V, 96h
- Biased DH: 85°C/85% RH, –1000V, 48h
- 25°C/50% RH,–1000V, Al-foil, 168h

The recent IEC draft 62804 Ed. 1.0 is based on the first of these parameter combinations. Although PI-Berlin employs all three of the different test conditions, most benchmarking data exist for the 85°C/85% RH condition (Fig. 5), leading to the conclusion that, in 2012, the majority of panels tested from different suppliers were still PID sensitive.

At the moment there are different ongoing activities aimed at round-robin testing for selected tests, comparing different test methods and correlating indoor and outdoor data, for example:

- PID round-robin testing based on IEC draft 62804 (system-voltage durability qualification test for crystalline silicon modules), coordinated by the National Renewable Energy Laboratory (NREL).
- PID round-robin project coordinated by PI-Berlin, focusing on the comparison of 60°C/85% RH/–1000V with 85°C/85% RH/–1000V and on the correlation of indoor testing and outdoor field degradation.

Impact parameter for PID – module and system design

When discussing PID with respect to risk mitigation by design, three different levels have to be distinguished:

1. Cell level
2. Panel level
3. System level / field

A PID-sensitive cell is a precondition for the observation of PID at the panel level. The cell level has already been presented by PI-Berlin in this journal [6], so the focus now will be on a discussion of the panel and system levels.

Panel level

When the solar cell specification allows for an accumulation of Na^+ ions within the SiN-ARC and a resulting interaction with the p-n junction (inverted emitter) [7], it is crucial whether or not panel design allows sufficiently high leakage current in order to support ion transport within the panel. Since the Na^+ ions from the glass are essential here, of the leakage current paths illustrated in Fig. 6 the one via the glass surface to the cell is the most important. This is supported by results from NREL, among others, which showed no evidence of the occurrence of PID in the case when Na^+ ions are absent from the front glass [8].

The general impact of the encapsulation material on the level of leakage current and therefore on PID has already been presented [1], showing that the electrical properties of the different material types play a key role. From recent measurements as shown in Fig. 7 it can be seen that bulk resistivity not only differs significantly for different material types, but also varies by about one order of magnitude between different EVA suppliers using different formulations.

The right choice of material combinations in production can therefore effectively suppress PID at the panel level by simply suppressing Na^+ ion transport to the cell. One option is to eliminate the Na^+ ion source in the first place, but probably an easier and less costly solution is to use high-resistivity encapsulation material.

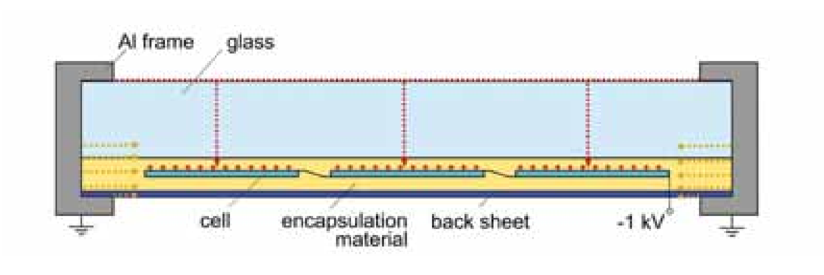

Figure 6. Leakage current paths in PV panels (adapted from Osterwald et al. [9]).

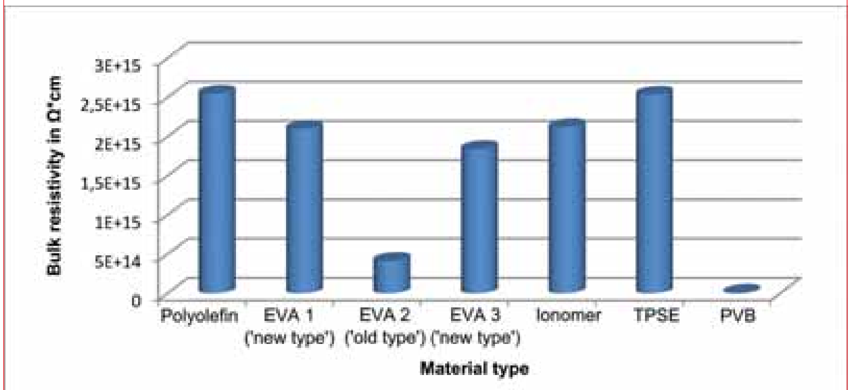

Figure 7. Comparison of bulk resistivity for different encapsulants.

System level

For PID to occur and be observed in solar installations a certain potential relative to ground must obviously exist. This potential depends not only on the system configuration but also on the specific panel position, as illustrated in Fig. 8. As a consequence, the power degradation in PID-sensitive panels depends on the type of grounding and the panel position within the panel string.

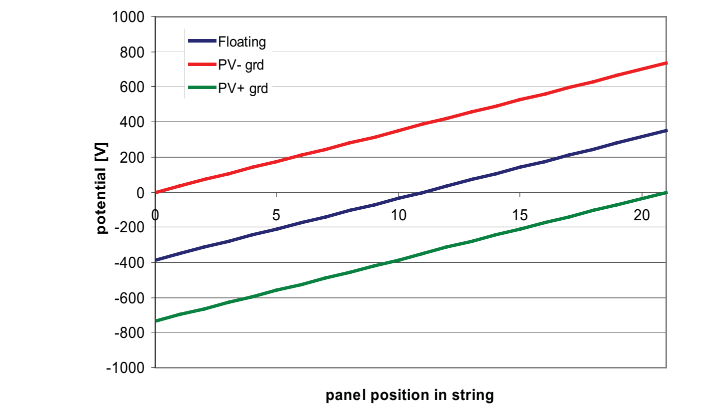

Figure 8. Potential relative to ground as a function of panel position and system configuration (functional grounding of either negative or positive poles, and no functional grounding or 'floating potential').

Because of the inverter concepts that are commonly used in solar plants, the most frequent configuration is the absence of a functional grounding of one of the poles, resulting in a so-called 'floating potential.' In Fig. 9 an example is given for the power loss due to PID as a function of the panel position for a panel string at a solar plant in southern Italy. As expected, the power loss increases with increasing (negative) potential relative to ground.

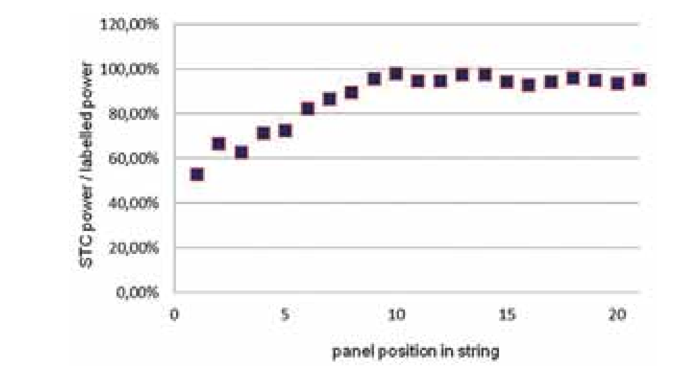

Figure 9. Power loss due to PID as a function of panel position (position 1 = closest to the negative pole).

In order to identify and analyze in-field PID, power measurements alone are usually not sufficient and are often not practical as the only investigation method for large-scale solar plants. Infrared (IR) inspection (Fig. 10) and electroluminescence (EL) analysis (Fig. 11) have been proved to be suitable extensions

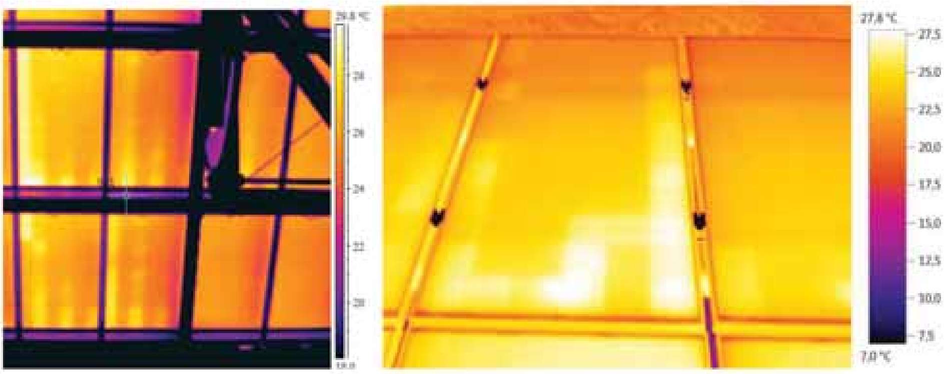

Figure 10. IR images of PID-affected panels in the field.

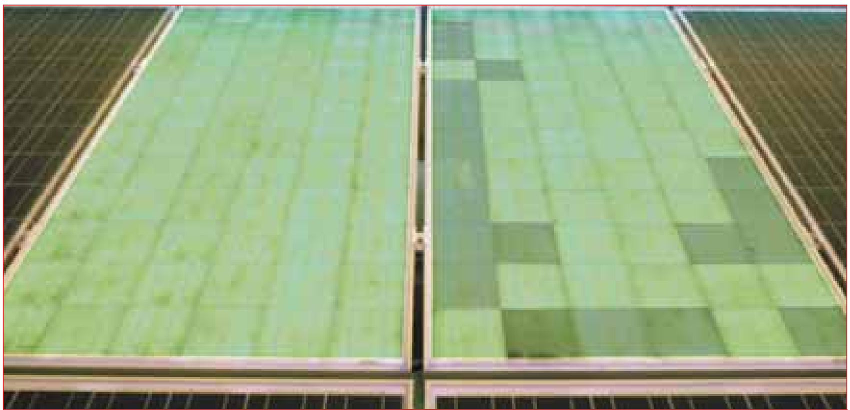

Figure 11. EL image of PID-affected panels in the field.

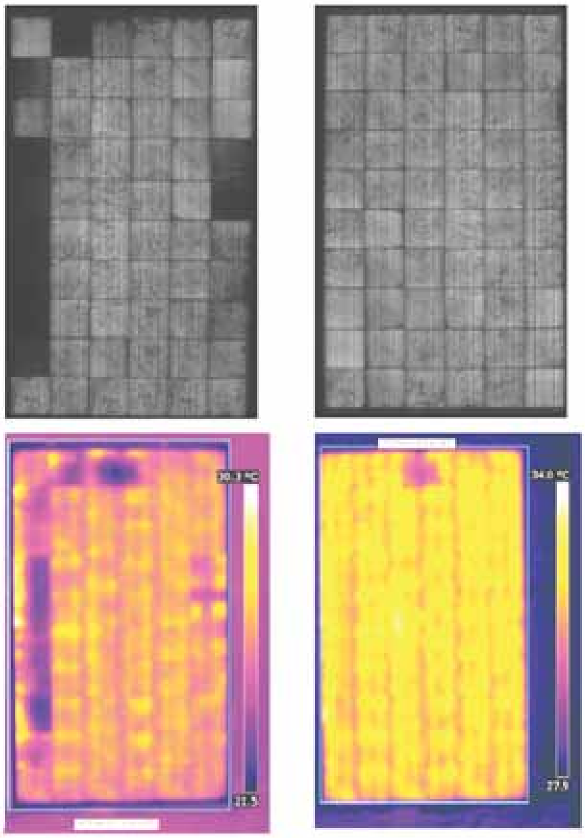

Figure 12. Complete recovery of PID field panels in a lab test: EL/IR images for PID field panels (left); EL/IR after recovery (right).

for PID investigations in the field. IR inspection in particular is useful for obtaining a (comparatively) quick estimate of the total number of PID-affected panels within a MW plant.

Recovery

As discussed earlier, PID is usually limited to the negative part of the string and can be avoided by a functional grounding of the negative pole. Owing to its principal reversibility it is also possible, under certain conditions, to recover from PID by 'removing' the negative potential, for example by reversing the potential or by functional grounding [1].

However, PID is not always completely reversible. Recovery time and extent depend not only on environmental factors but also on the degree of PID in the first place and therefore on the 'history' of the panel. Whether or not PID can be recovered from in the field by suitable measures has to be decided on the basis of recovery test results of PID-affected panels from a specific plant. For this purpose PI-Berlin is conducting both indoor and outdoor recovery tests for PID field panels.

> "Recovery time and extent depend not only on environmental factors but also on the degree of PID."

For an indoor test the maximum extent of recovery is determined under defined conditions, whereas for an outdoor installation it is determined under realistic environmental conditions. Fig. 12 shows PID field panels before and after recovery at 85°C/85% RH/–1000V.

In Fig. 13 the outdoor recovery results for different PID field panels, however, show a comparatively high recovery rate at the beginning, and a significant slowdown towards the end. In this example, recovery has not yet been completed, although there

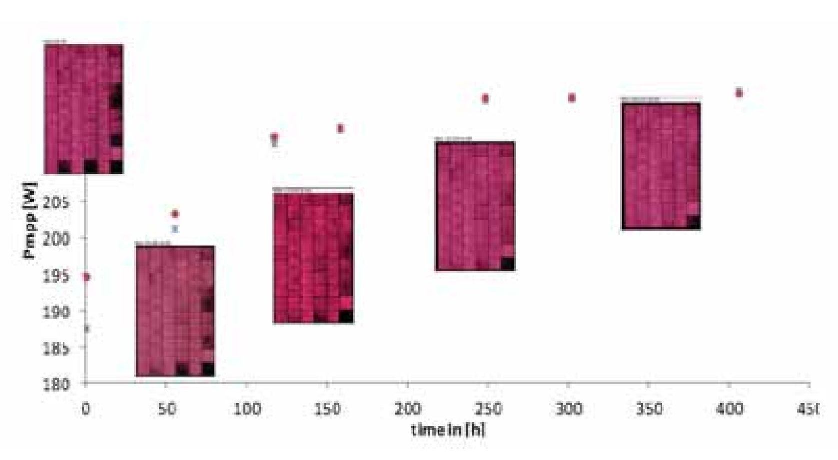

Figure 13. Performance under standard test conditions (STC) as a function of outdoor PID recovery time.

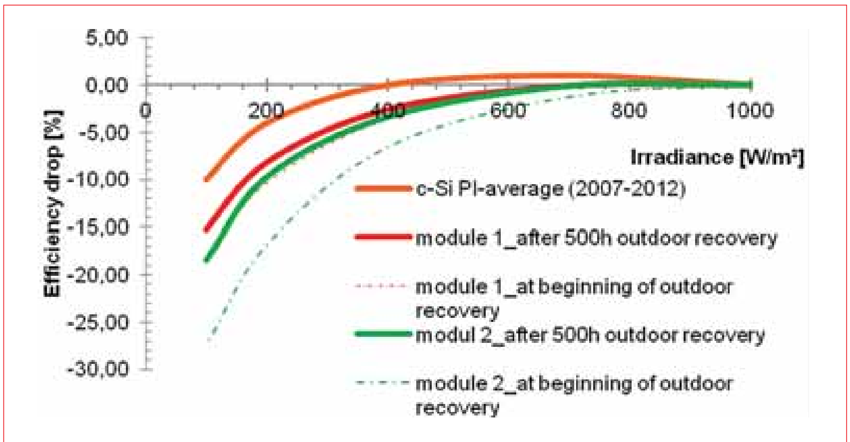

Figure 14. Recovery of weak-light performance of PID field panels compared with PI-Berlin average.

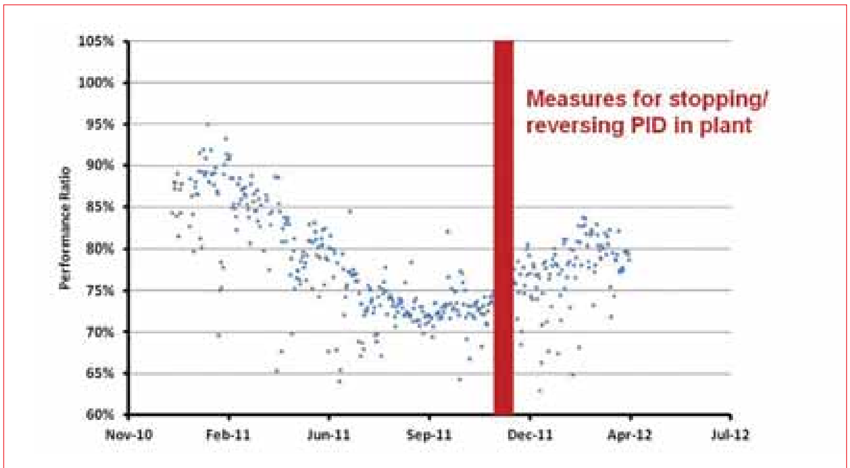

Figure 15. Performance ratio (PR) trend before and after PID measures were taken for the affected CT unit in the plant.

was no observed increase in power over a longer period of time (around three weeks).

Whereas the degradation had taken place within five months (until May 2012) in a solar plant in southern Italy, the recovery in an outdoor installation in Berlin at +400V for nine hours during the day was not yet fully completed after six weeks (August/September 2012) and power was still lacking.

Another aspect that should be mentioned with respect to recovery is the weak-light performance of PID field panels. With weak-light performance being even more affected in the first place than STC power, it should also be pointed out that, because the shunt resistivity usually remains at a lower level than previously, the weak-light performance tends to remain 'beyond' STC power recovery, as shown in Fig. 14 for two PID panels undergoing outdoor recovery.

PID in the field

In order to tackle PID in the field, PI-Berlin has developed a programme consisting of two parts:

1. An analysis of panels from the suspicious plant.
2. An in-field analysis and monitoring of measures taken.

In the first part, affected panels from the plant are investigated with respect to degradation and recovery behaviour. Once PID is confirmed in the lab, the second part focuses on the specific solar plant affected. Ideally, 'unusual' units or strings in the plant can be already identified by analyzing data from the plant-monitoring system, which can be accessed remotely. This is then followed by in-plant measurements, which – together with the results from part 1 – will lead to certain recommendations regarding suitable measures for the specific plant. The measures taken will then be monitored by repeated in-plant measurements.

> "PID on a large scale in a solar plant can significantly affect performance ratio."

PID on a large scale in a solar plant can significantly affect performance ratio (PR). Although this is only a very rough and nonspecific criterion for PID, from the point of view of investors and owners it is probably the most interesting one. In Fig. 15 the PR trend is shown for a PID-affected central transformer (CT) unit of a solar plant before and after suitable measures are taken.

After underperforming (CT) units have been identified in plant, measurements in plant are taken. Fig. 16(a) shows the results for a panel string in an East European plant. On the whole, the trend in power loss within a string due to PID was as expected: the closer to the negative pole of the string, the higher the power loss observed.

The trend within a panel string is not, however, always found to be 'ideal,' as shown in the diagram for a string in a Spanish solar plant (Fig. 16(b)), where there are obviously additional superimposed factors (e.g. inhomogeneous panel batches, additional potentials). The corresponding EL and IR images for these panels are shown in Fig. 17. A power loss of up to 30% was detected in this plant for the majority of the panels measured in the negative part of the string (Fig. 18).

The main goals, however, when tackling PID in the plant are obviously not just to describe and analyze the situation, but also to achieve a measureable improvement in performance, as illustrated in Fig. 19.

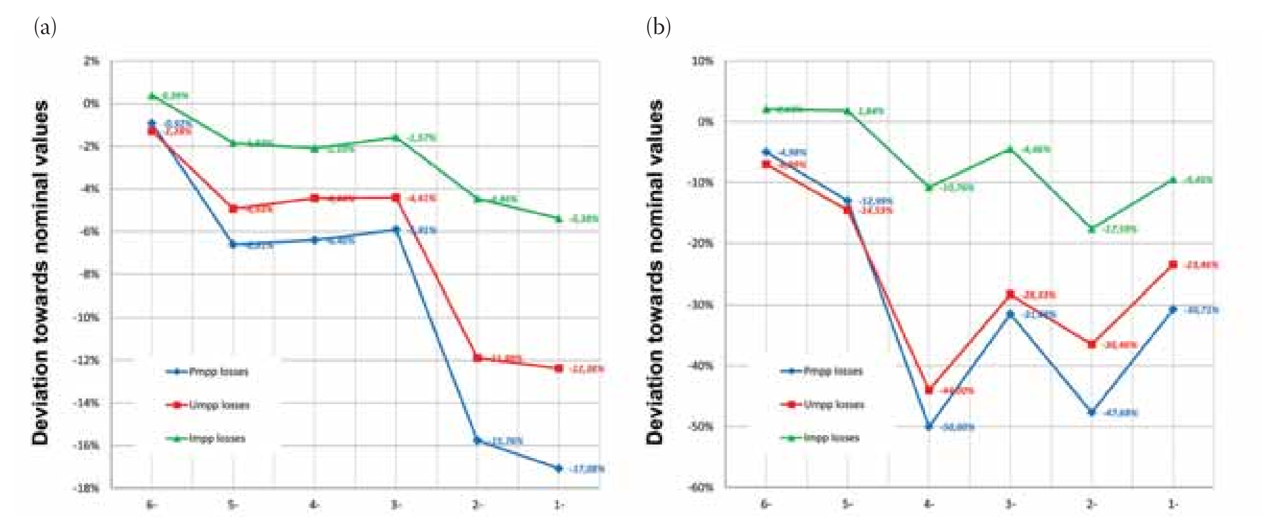

Figure 16. Power at the maximum power point (Pmpp) loss for panels in the negative part of the string depending on panel position ('–1' = closest to negative pole): (a) East European solar plant; (b) Spanish solar plant.

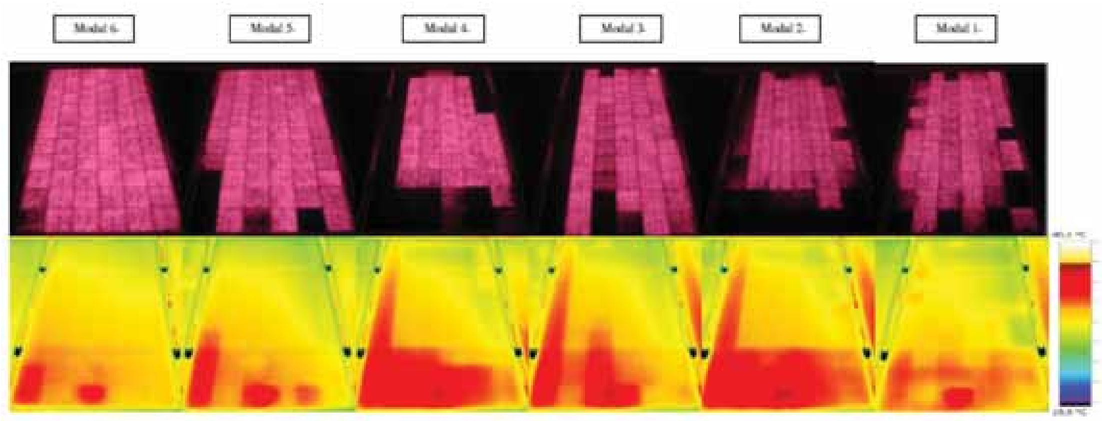

Figure 17. El and IR images for panels in a PID-affected string in the Spanish plant.

"A standard lab test is urgently needed in order to have comparable data from different test labs."

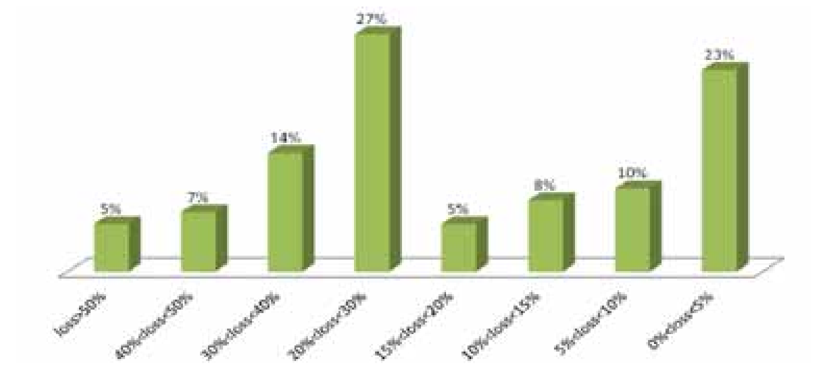

Figure 18. Distribution of the Pmpp loss for all the measured modules in the Spanish PID-affected plant.

Summary and conclusion

Although the majority of panels from different suppliers tested at PI-Berlin still show considerable PID in tests, it does not automatically mean that these panels will show significant PID once they are installed in the field. Additional factors, such as climate and weather conditions and the specific system configuration, play an important role in the occurrence of PID in the field.

Recovery from PID is possible by using suitable measures; however, the extent and rate of PID recovery in the field strongly depends on the outdoor conditions and on the degree of the initial PID. Weak-light performance of field panels is usually more affected than STC power, and the extent of recovery is often less.

Comprehensive measures for controlling PID have been taken by cell, encapsulation, panel and inverter suppliers, yet it is still not under control everywhere and is increasingly evident in the field. Accordingly, a standard lab test is urgently needed in order to have comparable data from different test labs.

Acknowledgement

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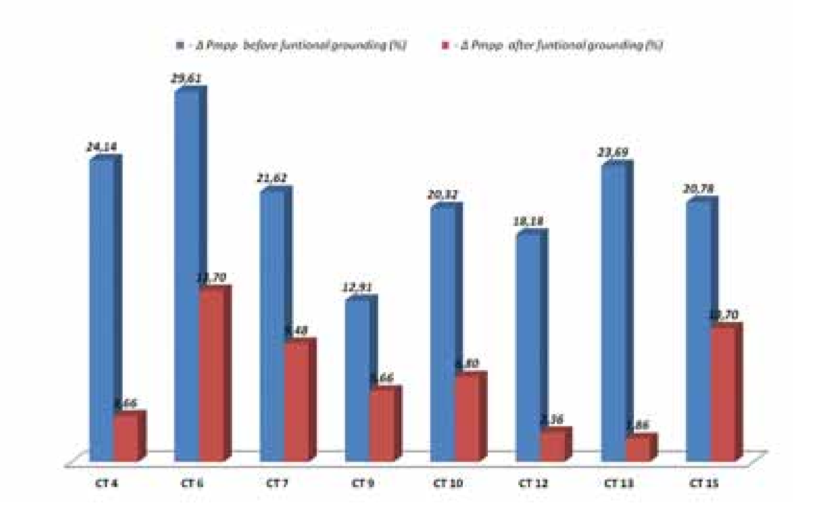

Figure 19. Trend for PID recovery (average values for panel power deviation for different CT units) in plant after functional grounding (time frame: May 2012 to Oct 2012).

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About the Authors

Juliane Berghold has been head of R&D at PI-Berlin AG since 2011. Prior to this she was director of R&D PV at SOLON, which she joined in 2006. Juliane received her Ph.D. in physical chemistry in 2002 and worked as a research associate on crystalline silicon thin-film technology at Helmholtz-Zentrum Berlin (HZB) until 2006.

Simon Koch joined PI-Berlin in 2007. He studied environmental engineering at the University of Applied Science in Berlin and received his diploma degree in 2008. For his diploma thesis Simon worked on defect analysis of silicon solar modules using electroluminescence and photoluminescence imaging, and is now focusing on PID simulation for his Ph.D. thesis.

Anja Böttcher studied renewable energies at the University of Applied science in Berlin and received her Master of Science degree in 2008. For her master's thesis she investigated the angular dependence of irradiation on performance for different cell technologies and glasses. Anja joined PI-Berlin in 2008 and is now a project manager of outdoor and field projects in R&D.

Asier Ukar studied mechanical engineering at TU Bilbao (ETSII Bilbao, Spain) and received his diploma degree in 2008 from TU Karlsruhe (Germany), specializing in power engineering and project management. Asier joined PI EXPERTS as part of the PI group in 2008 and is a project manager, working on outdoor and system-integrated projects.

Mathias Leers studied environmental engineering/renewable energy systems at the HTW Berlin and received his Master of Science degree in 2010. Mathias worked in the PI Laboratory before joining PI EXPERTS in 2011, where he is a project manager, involved in planning, expertise and outdoor measurements.

Paul Grunow received his Ph.D. in physics from TU Berlin in 1993 for his work on silicon solar cells at the Helmholtz Centre Berlin. Following a postdoctoral post in Rio de Janeiro in Brazil (UFRJ-COPPE), working on solar thin-film materials, he co-founded SOLON AG in 1996. Together with Reiner Lemoine and others, Paul co-founded Q-Cells AG in 1999, and in 2006 he co-founded PI-Berlin, of which he is a member of the board and senior consultant.

Enquiries

Dr. Juliane Berghold
Head of R&D
Photovoltaik-Institut Berlin AG
Wrangelstr. 100
D-10997 Berlin
Germany

Tel: +49 (30) 814 52 64 120
Fax: +49 (30) 814 52 64 101
Email: berghold@pi-berlin.com
Website: www.pi-berlin.com