Shunting-type potential-induced degradation: How to ensure 25 years' service life

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ABSTRACT

Potential-induced degradation (PID) of the shunting type (PID-s) is one of the most severe forms of PID, which is caused by the negative potential of p-type solar cells with respect to grounded frames/mounting. Although this negative potential can be completely avoided at the system level, that is not the case for a large number of modern PV systems. PV modules that are able to sustain PID-s stress for at least the duration of their service life are therefore essential. To assess whether modules fulfil this requirement, laboratory tests are currently recommended in which the modules are exposed to a certain constant level of PID-s stress for a given amount of time. These types of test with constant stress levels, however, are only feasible in the case of degradation mechanisms that are not reversible in the field, for which non-coherent stress episodes simply sum up to the total stress. Unlike other mechanisms, PID-s is reversible under field conditions; as a consequence, the level of PID-s of a fielded module is the result of an intricate interplay of phases of degradation and regeneration. This behaviour cannot be replicated in a laboratory test using a constant stress level; the currently recommended laboratory tests for PID-s with constant stress levels are therefore not appropriate for assessing the service life duration, and can only be used for differentiating the susceptibility to PID-s stress and for monitoring the stability of production processes. For monitoring the PID-s resistance of its products, Hanwha Q CELLS uses tests for PID-s with constant stress in accordance with the draft for IEC PID test method 62804. This assures that all the products of the Q CELLS brand come with Anti-PID Technology (APT). The expected service life duration with respect to PID-s is assessed by simulating the interplay of degradation and regeneration under non-constant outdoor conditions that are based on meteorological data.

Introduction

A PV system collects the energy of sunlight, and the challenge is to extract as much of the collected energy as possible in the form of electrical power for use in various applications. Electrical power is the product of current and voltage; in other words, providing electrical power means providing a current flow together with a voltage difference. Consequently, high currents or voltages have to be present in PV systems in order to obtain a high electrical power output; this means that the constituent parts are subject to a certain level of stress.

In order to keep conduction losses due to current flow as small as

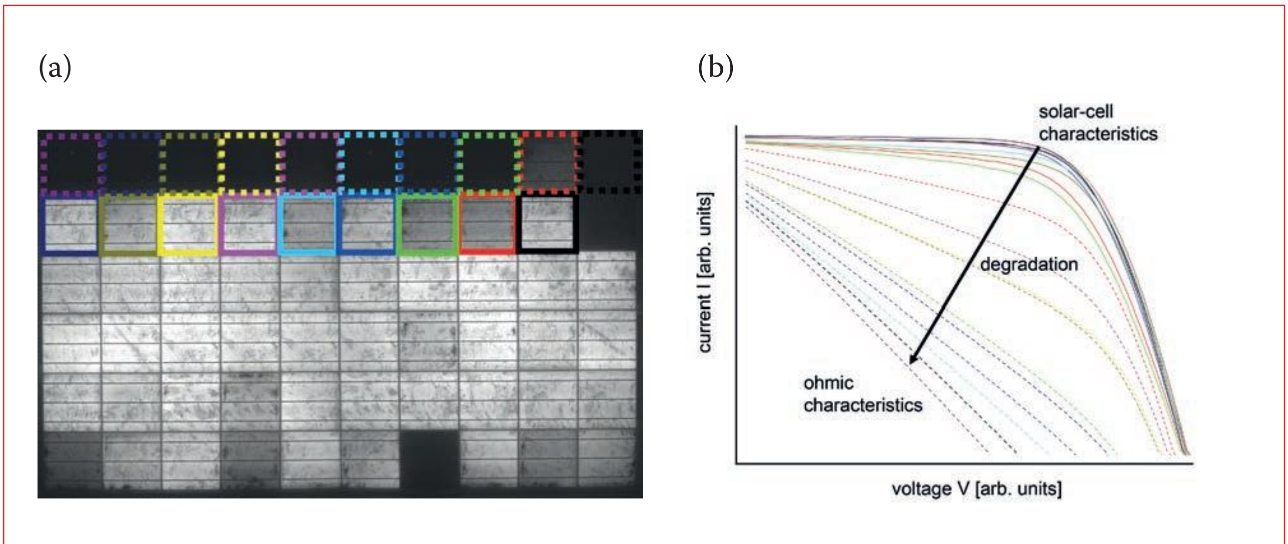

Figure 1. Shunting of solar cells because of PID-s: (a) electroluminescence image of a PID-s affected module; (b) *I*–*V* characteristics of individual cells that have degraded to different degrees, showing the evolution of PID. The coloured boxes in (a) correspond to the lines in (b) (low PID-s: solid boxes/lines; high PID-s: dashed boxes/lines). (Adapted from Schütze et al. [8].)

possible, there is a continuing trend to obtain high voltages in modern PV systems by connecting more and more modules in series, in so-called *module strings*. Increasingly large differences in the electrical potential of different system parts therefore occur, leading to increased stress levels of the constituents. Special care must be taken if those differently biased parts are positioned close to each other; this is the case, for instance, with PV modules, which usually contain electrically active elements, such as solar cells, and electrically passive (but nevertheless conducting) ones such as metal frames. Potential differences of several hundred volts can be present between those elements within a space of a few millimetres, as the metal frames have to be grounded for safety reasons.

Since the electrical isolation of the different parts is not perfect in practice, large potential differences cause parasitic leakage currents, which can lead to so-called *potential-induced degradation (PID)*. The leakage currents responsible for PID will decrease dramatically with increasing distance of the differently biased parts. The distance of the electrically active parts from the grounded frame can be as little as a few millimetres at the edge of a module, but as much as a few decimetres in the middle of the module. The leakage current, and thus the PID stress, in the case of a large distance will be negligible compared with that in the case of a small distance. Under dry conditions, PID stress will therefore be present only in the outermost regions of the module surface. This situation changes dramatically when rain or dew is present, which make the module surface conductive. Large parts of the module surface can be at the same potential (ground) as the module frame in this case, which leads to almost constant high leakage currents and PID stress for those parts of the module that are wet.

Various kinds of module defect caused by PID have been reported – for example, electrochemical corrosion [1], delamination [2,3] and passivation breakdown [4]. PID, however, seemed to have been limited to thin-film modules [1–3] and specialized cell concepts [4] until 2007; the first case of PID for standard silicon-wafer-based solar cells was reported in 2008 [5]. Awareness of PID began to increase rapidly in 2010, when it became apparent that a certain type of PID can affect all modules containing standard p-type solar cells [6,7]. For differentiation purposes, this effect is called *PID of the shunting type (PID-s)*, since it leads to shunting of the solar cells [8] (Fig. 1). Because of shunting, the generated electrical power cannot be extracted from the solar cells – it is already dissipated within them.

"PID-s can occur when solar cells are exposed to a negative potential with respect to the frame/mounting."

PID-s can occur when solar cells are exposed to a negative potential with respect to the frame/mounting. In today's PV systems, commonly used inverter concepts often result in a so-called *floating potential*, because of the absence of a functional grounding of one of the poles. With a floating potential present, half of a module string is exposed to a negative potential, and therefore to PID-s stress. The PID-s stress increases from the middle of the module string towards the negative pole, while the positive string part remains unaffected, as illustrated in Fig. 2.

The potential distribution as a function of module position in a PV module string with a floating potential present is schematically shown in Fig. 2(a); the resulting PID-s stress that the individual modules are exposed to (red colour), depending on their position in the string, is shown in Fig. 2(b). Note that the indicated homogeneous stress levels for the individual modules are present for wet conditions, leading to a conductive front surface of the modules, only. For dry conditions, only

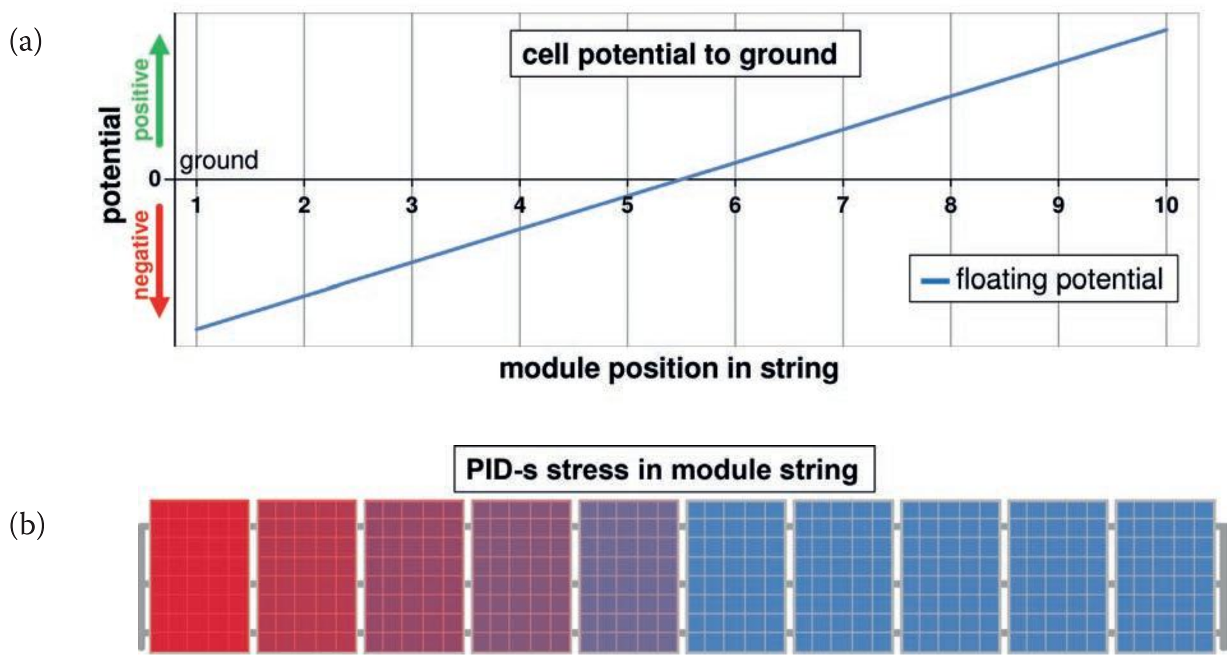

Figure 2. Dependence of PID-s stress on the module position in a string: (a) potential distribution as a function of the module position in a string with a floating potential; (b) resulting PID-s stress (indicated in red) for the individual modules of the string in the case of wet conditions, leading to a conductive front surface. For dry conditions, only the outermost parts of the modules will be exposed to the indicated stress levels, which is usually not sufficient to cause a substantial power loss of the modules.

the outermost parts of the modules will be exposed to the indicated stress levels; this is not believed to usually be sufficient to cause a substantial power loss of the modules from PID-s. Nevertheless, wet conditions (rain or dew) resulting in sufficient stress will always be present during certain periods of time in a field installation. In the case of PV modules that are susceptible to PID-s, this stress can lead to catastrophic power [6,7] and yield [5] losses.

At the microscopic level, the PID-s of the solar cells originates from the migration of sodium ions to the front of the cell. It has been shown that sodium accumulates at the cell surface and attaches to stacking faults that are present in the silicon material [9]. These stacking faults extend from the silicon surface, through the n-type emitter layer, to the p-type bulk of the cell. The sodium accumulation is believed to result in a conducting pathway, shunting the p-n junction [9].

Mitigation possibilities – Anti-PID Technology (APT)

There are a number of different ways to avoid PID-s. Since a negative potential of the solar cells with respect to the frames/mounting is necessary for PID-s to occur (Fig. 2), it is possible to avoid PID-s at the system level by grounding the negative pole of the individual module strings; the solar cells are then always at a positive potential with respect to ground. Unfortunately, most inverters without transformers cannot be grounded this way, because of their architecture; however, by using slightly less-efficient inverters with transformers, it is generally possible to ground the negative pole of the module strings. Most of these inverters are not yet grounded at the mounting. This leads to a floating potential, with half of the module string frequently exposed to PID-s stress (Fig. 2), that can then simply be eliminated by proper grounding.

A second option to avoid PID-s stress is at the module design level, and there are several solutions possible here. Protection from PID-s can be achieved by omitting the metal module frame [10], which has to be grounded for safety reasons. Without a grounded frame, a wet module glass surface will not be in contact with the ground potential, and therefore no potential difference can build up between the solar cell and the front side of the module glass. For standard glass–foil laminates, however, it is difficult to ensure a sufficient stability of the modules without a frame. On the other hand, in the case of glass–glass modules, a frameless design with a back-rail mounting can be feasible. Another possible measure to prevent PID-s is to increase the PID-s resistance by preventing the drift of sodium ions to the cell surface; this can be done by using a high-resistivity sodium-free glass, but such an option is usually cost prohibitive. An easier and less-costly solution is the mitigation of the sodium drift by high-resistivity encapsulation materials [7,8,11,12].

A third option for PID mitigation is at the cell level. Here, PID-s resistance can be achieved by a proper selection of materials in conjunction with optimized design and adjusted cell processes. For instance, it has been suggested that a high refractive index of the silicon nitride (SiN_x) films that are commonly used as an anti-reflection coating (ARC) can prevent PID-s [6,11]. Unfortunately, however, a high refractive index of SiN_x comes with a high light absorption of the ARC films, which reduces the conversion efficiency of the solar cell [11].

The challenge is to find a set-up that successfully prevents PID-s while maintaining the electric cell performance at an excellent level. A combination of materials and process/design parameters which ensures that cells deliver both excellent electrical performance and resistance to PID-s has been implemented by Hanwha Q CELLS – Anti-PID Technology (APT), which comes with all products of the Q CELLS brand.

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Testing for PID

Many laboratory PID test methods have been proposed in recent years for verifying and quantifying the PID-s resistance of PV modules. The most common test conditions are:

- Biased damp heat (DH): 60°C/85% RH, module rated system voltage bias (commonly –1kV), 96h.
- 25°C/RH < 60%, module rated system voltage bias (commonly –1kV), grounded Al foil covering the module glass, 168h.
- Biased damp heat (DH): 85°C/85% RH, –1kV, 48h.

The first two test conditions are part of the draft for an IEC PID test method (IEC TS 62804). All these tests have in common the fact that a certain constant stress level is applied continuously for a given amount of time.

These types of laboratory test method are usually applied in order to assess the service life with respect to a particular degradation mechanism. To be feasible, the methods are generally limited with respect to the possible test time and the permitted costs. Simple test methods are desirable which ideally apply the same amount of stress that the module would be exposed to during its desired service life, but in an accelerated manner, i.e. preferably over a period of days or weeks. In the case of most non-reversible failure modes, such as corrosion or mechanical stress issues, the stress a module is exposed to during its service life can be cumulated; this makes it possible to carry out laboratory tests corresponding to service life by applying the same cumulated stress. In principle, the tests can be performed continuously at a constant stress level, and the stress level can often be even higher than in the field. These measures allow the application of the desired cumulated stress in a time much shorter than the service life.

In the following discussion it will be shown that PID-s is a complex failure mode which is reversible under field conditions. For reversible failure modes, however, it is not justified to cumulate the service life stress as can be done for non-reversible failure modes. A simple laboratory test method with continuous and constant stress therefore cannot assess the service life behaviour of a fielded PV module with respect to PID-s.

Nevertheless, PID-s laboratory test methods, like the ones mentioned above, are widely accepted as methods for verifying the stability of the production process and the product quality. Since these methods apply a constant and reproducible PID-s stress to a PV module, the changes in product quality can be revealed by a change in behaviour under PID-s stress. In order to ensure its standards of high quality for all Q CELLS-branded products, Hanwha Q CELLS has established a PID monitoring process in which production samples are tested on a monthly basis using the aluminium foil test described in the draft of the IEC PID test method (IEC TS 62804). In addition, a similar test is also carried out on a weekly basis at the cell level. The results of monitoring module production in 2014 are shown in Fig. 3; the fail criterion (power loss > 5% at standard test conditions – STC) is indicated by a red dotted line. This monitoring is a part of Q CELLS' APT and allows the assurance that APT really is continuously provided with the products of the Q CELLS brand. Since the implementation of APT, including the monitoring process, there have been no PID-s claims relating to Q CELLS-branded products, confirming the excellent level of resistance to PID-s.

The complexity of PID-s kinetics will be presented next, and the resulting PID-s behaviour of modules under outdoor conditions will be demonstrated in order to point out the limitations of laboratory PID test methods with respect to PID-s.

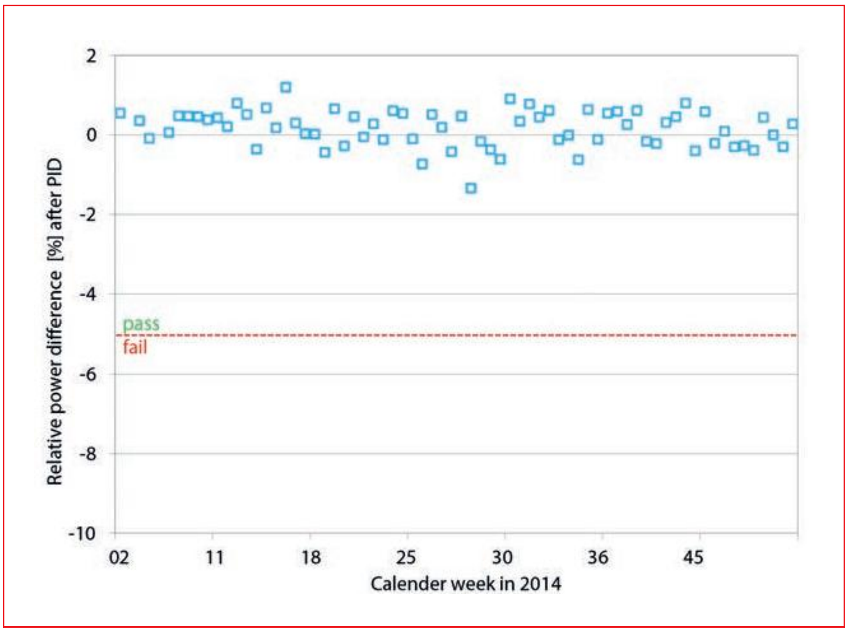

Figure 3. Process control of Q CELLS' module production: weekly monitoring data for 2014.

PID-s and regeneration

The kinetics of PID-s has recently been studied in detail [13–17]. It has been shown that the shunt resistance (R_{sh}) of the solar cell can be used as an early-warning parameter for monitoring the PID-s kinetics. This parameter is highly sensitive to PID-s stress and allows the investigation of the PID-s behaviour of a solar cell long before the onset of power loss. An implied fill factor $FF_{implied}$ can be calculated from R_{sh} [18] in order to estimate the resulting power loss at STC; a significant STC power decrease is only present for values of $R_{sh} < 2k\Omega cm^2$.

In Fig. 4 R_{sh} measurements over time for two different one-cell mini-modules are shown, as recorded in a laboratory test at a constant temperature. The mini-modules were exposed to PID-s stress by covering the glass surface with a grounded aluminium foil and exposing the solar cell to a bias voltage of –1kV relative to ground. The PID-s stress was terminated by switching off the bias voltage.

The R_{sh} values for both mini-modules decrease from the very second the bias voltage is applied, revealing the effect of shunting caused by PID-s; this phase is called the *shunting phase S* (red area in Fig. 4). After the bias voltage is stopped, R_{sh} continues to decrease along the red curve while slowing down, finally levels off and then starts to increase again. The phase starting from the point at which the bias was stopped until the value of R_{sh} at which the bias voltage has been stopped ($R_{sh,bvs}$) is reached again is called the *transition phase T* (blue area in Fig. 4). The duration of this T phase can vary for different types of solar cell and/or module. PV modules may also have no T phase at all, which is the case

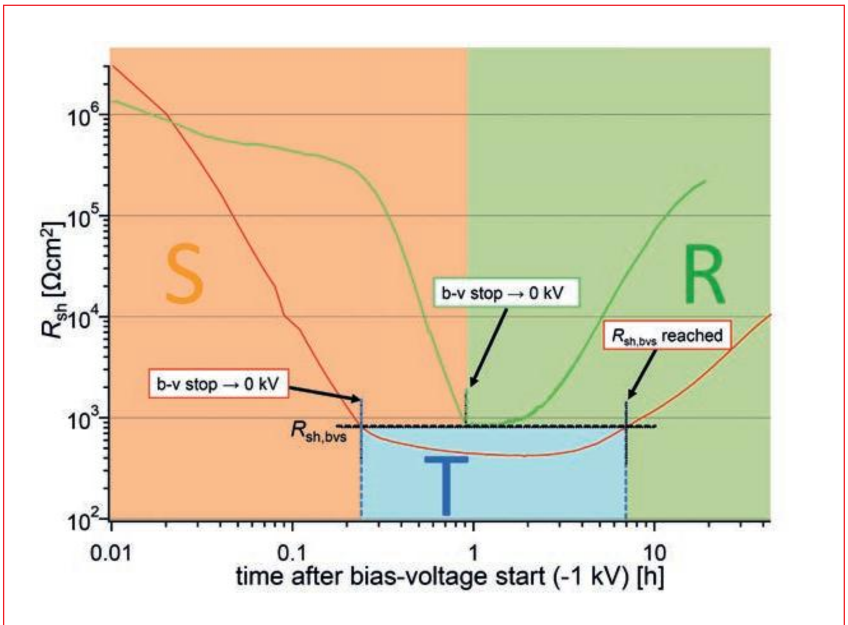

Figure 4. Shunt resistance (R_{sh}) measurements during shunting and regeneration: laboratory measurements for two different one-cell mini-modules at a constant temperature as a function of time after bias voltage (b-v) start (green curve and red curve). The R_{sh} value at the b-v stop ($R_{sh,bvs}$) is indicated by a dashed horizontal black line. The shunting (S), transition (T) and regeneration (R) phases are highlighted by the red, blue and green areas respectively. The green curve exhibits no T phase, in contrast to the red curve.

for one of the mini-modules, indicated by the green curve in the figure.

The following phase, in which the R_{sh} value increases above $R_{sh,bvs}$, is called the *regeneration phase R* (green area in Fig. 4). Regeneration from PID-s has also previously been observed in the field [10,16,17]. It has been found that the shunting, T phase passage and regeneration rates increase exponentially with increasing temperature [13,14]. Between different types of solar cell and/or PV module, the rates observed in the S, T and R phases can vary significantly; this leads to a variation in the resistance to PID-s of PV modules in the field.

PID-s of fielded modules

PID-s stress in fielded modules, even at the negative side of a PV module string, is not always present: only if certain environmental conditions are met is a module subject to PID-s. The key condition is a conductive front surface of the module in the presence of sunlight. Without sunlight (i.e. at night-time), the system is not generating power; no potential difference at all will therefore be present in this case. If, in the daytime, the front surface of the module is not conducting, the potential difference between the grounded frame/mounting of the module and the cells will not be able to drive a leakage current sufficiently large to have a harmful effect, because of the high resistivity of the glass surface [19].

The front of the module can become conductive under certain field conditions by water deposition in the event of morning dew or rain. At night-time, and in the daytime without a wet glass surface, a PV module will therefore generally be free from PID-s stress.

A module – after a transition phase if applicable – will recover from power degradation in the absence of PID-s stress [10,13–17]. This results in an intricate interplay between PID-s and regeneration for fielded modules, which is illustrated in Fig. 5. The upper graph shows schematically the PID-s stress that a PV module mounted at the negative string side is exposed to during two sample days. On the first day, there is only one PID-s stress event present, caused by morning dew. On the second day, two PID-s stress events are assumed, one again caused by morning dew, and the second resulting from a short shower in the daytime. During the shower event, the module temperature is elevated compared with the morning dew events; this results in a significant increase in PID-s stress. For simplification purposes, in this example the temperatures during the daytime and night-time are assumed to be constant; the daytime temperatures on the two days are also assumed to be the same, as are the two night-time temperatures.

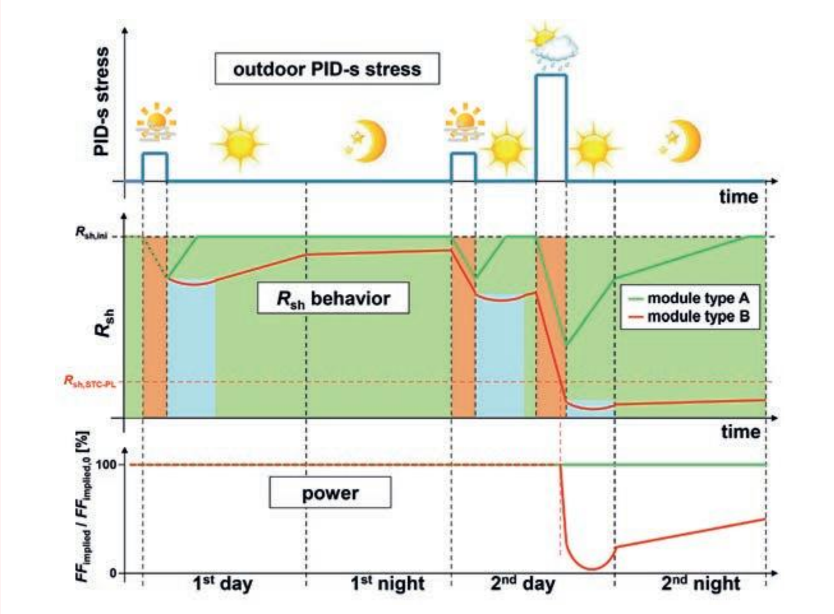

Figure 5. Outdoor PID-s stress and R_{sh} behaviour: the upper graph illustrates the PID-s stress that a fielded PV module is exposed to, mounted at the negative potential side of a module string during two sample days. The resulting R_{sh} behaviour for two different PV module types A and B is shown in the centre graph, by the green and red lines respectively. The S, T and R phases of the R_{sh} kinetics are represented by the red, blue and green areas respectively. The initial R_{sh} value ($R_{sh,ini}$) and the R_{sh} value of the STC power loss onset ($R_{sh,STC-PL}$) are indicated by horizontal dotted black and red lines respectively. A red dotted vertical line marks the start of significant power loss for module type B; this becomes more apparent in the lower graph, which shows the $FF_{implied}$ behaviour that is indicative of the actual power loss.

The centre graph in Fig. 5 illustrates the resulting R_{sh} behaviour of two different PV module types A and B, as a function of time, while the lower graph shows the corresponding $FF_{implied}$. The R_{sh} kinetics of module type A, represented by the green line, is assumed to exhibit no T phase, and a favourable regeneration behaviour. The R_{sh} kinetics of module type B, represented by the red line, is assumed to show a T phase and a less-favourable regeneration behaviour. It is further assumed that the shunting rates of the two module types are similar and that the initial shunt resistances ($R_{sh,ini}$) are the same.

As a result of the morning dew at the beginning of the first day, an S phase (red area) is present, leading to a decrease in R_{sh} for both module types. The S phase ends with the evaporation of dew, and the R phase (green area) and the T phase (blue area) begin for module types A and B respectively. Eventually module type B exits the T phase and reaches the R phase as well. Note that module type B generally demonstrates a slower regeneration rate than type A. During the first night, the R phase continues at a lower temperature, leading to a slowdown in the increase in R_{sh} for module type B. At this time, module type A has already completely regenerated.

At the beginning of the second day, an S phase is again present, followed by R and T phases, as on the first day. Note that, until this point, there have been no substantial power losses for both modules, as indicated by the virtually constant $FF_{implied}$. The R phase is then interrupted by a rain event in the daytime, leading to an S phase with an increased PID-s stress because of the increase in temperature. During the rain event, the R_{sh} value of the solar cells incorporated in module type B decreases below the onset value for STC power loss ($R_{sh,\,STC\text{-}PL}$), which marks the beginning of the power loss of module type B. This becomes more apparent in the $FF_{implied}$ curve, which indicates an abrupt decrease for module type B. A comparison of the centre and lower graphs reveals the early-warning character of R_{sh}, while $FF_{implied}$ is the most appropriate for evaluating the drop in STC power.

After the rain event, module type B again passes the T phase and eventually reaches the R phase. In spite of the R phase, module type B is not able to sufficiently regenerate, resulting in a major power loss at the end of the two-day period. Module type A, exhibiting a more favourable regeneration rate and no T phase, experiences only a moderate R_{sh} decrease during the rain event and a rapid R_{sh} increase afterwards. The R_{sh} value is well above the $R_{sh,STC\text{-}PL}$ at all times, and at the end of the second night it has reached its initial value again. The $FF_{implied}$ curve for module type A therefore remains virtually unaffected, indicating no significant power decrease during the two sample days.

In summary, module type A is resistant to PID-s because of favourable shunting/regeneration behaviour. The PID-s resistance of module type B, however, is not high enough, as a result of unsatisfactory shunting/regeneration behaviour.

Note that in this example both module types demonstrated the same shunting behaviour. Simple laboratory test methods, such as those previously described, would not distinguish the difference in the PID-s behaviours and thus in the PID-s resistances. Those tests cannot therefore be used to determine the reliability of PV modules with respect to PID-s. Accordingly, a laboratory test method cannot predict the resistance to PID-s of modules in the field that have passed tests.

It becomes apparent that the transition/regeneration behaviour of a PV module has a crucial impact on its PID-s resistance. The regeneration effect can also be used to counteract the effect of PID-s on a fielded module by, for example, employing a so-called *PV offset (PVO)* box [20] that applies a positive bias voltage overnight in order to boost regeneration. The disadvantages of this solution are the additional costs and the fact that the installation of the boxes is usually not done before a power loss of the system due to PID-s has been observed; this results in limitation of the loss, rather than prevention.

> "The transition/regeneration behaviour of a PV module has a crucial impact on its PID-s resistance."

By investigating the transition/regeneration behaviour together with the shunting behaviour of a PV module in detail, it becomes possible to assess its long-term behaviour in the field, and thus quantitatively determine its PID-s resistance. Hanwha Q CELLS has developed a PID-s model simulating the progression of R_{sh} under real outdoor conditions, taking into consideration shunting, transition and regeneration [14,15]. This model is used to predict the long-term PID-s behaviour of Q CELLS' products and to optimize the APT in such a way that no power loss is present during their service life. The PID-s model will be described next in more detail.

Modelling of PID-s

In the investigation of the long-term R_{sh} behaviour of a PV module, Hanwha Q CELLS began to simulate the PID-s progression under fluctuating environmental conditions, as present in the field. To deal with the fluctuating conditions, the time interval of interest – usually several years – is divided into small time steps, no larger than one hour; the time steps have to be small enough to justify the assumption of constant environmental conditions during those steps. The general process used to model PID-s is illustrated in Fig. 6; the simulation of the service life PID-s behaviour of a fielded module in a specific region is possible with this model.

a) Environmental data

Environmental data for the installation site during the time period of interest have to be obtained, including the ambient temperature T_{amb}, relative humidity RH_{amb} with respect to T_{amb}, solar irradiation on the module plane IR_{mod}, and information about when rain events occur. The model takes into consideration module temperature T_{mod}, relative humidity in the vicinity of the module RH_{mod}, and rain events. The module-specific data do not have to be measured directly but can be derived from meteorological data. If not measured, T_{mod} can be calculated from the measurements of IR_{mod} and T_{amb} by utilizing the nominal operating cell temperature (NOCT) [21]. RH_{mod} can be computed from T_{amb}, T_{mod} and RH_{amb} by using the temperature dependence of the saturation vapour pressure of water [19], which can be referenced in the literature.

b) R_{sh} kinetics and classification

Key to a PID-s model is the determination of the temperature-dependent R_{sh} kinetics in laboratory experiments – two examples of measured R_{sh} progressions of mini-modules were given in Fig. 4. Details regarding the R_{sh} kinetics and its analysis can be found in the literature [13–15]. IR_{mod} and RH_{mod} data are used to assign one of the three phases S, T or R to every

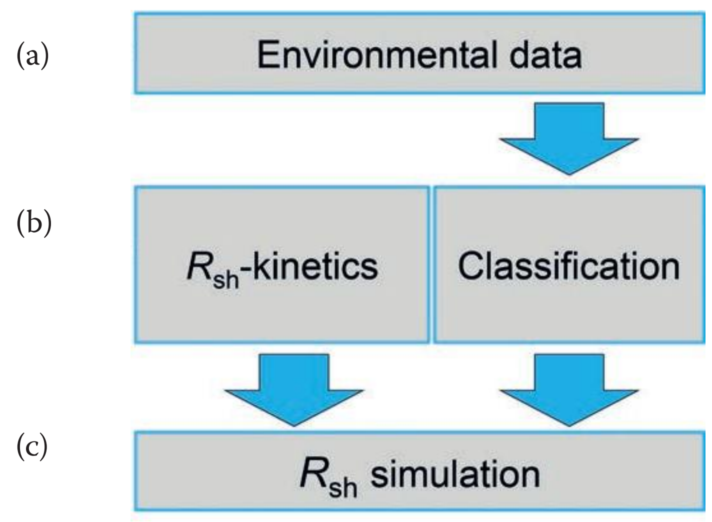

Figure 6. Illustration of the PID-s model procedure: the concept of modelling the long-term R_{sh} behaviour under outdoor conditions. (Adapted from Taubitz et al. [15].)

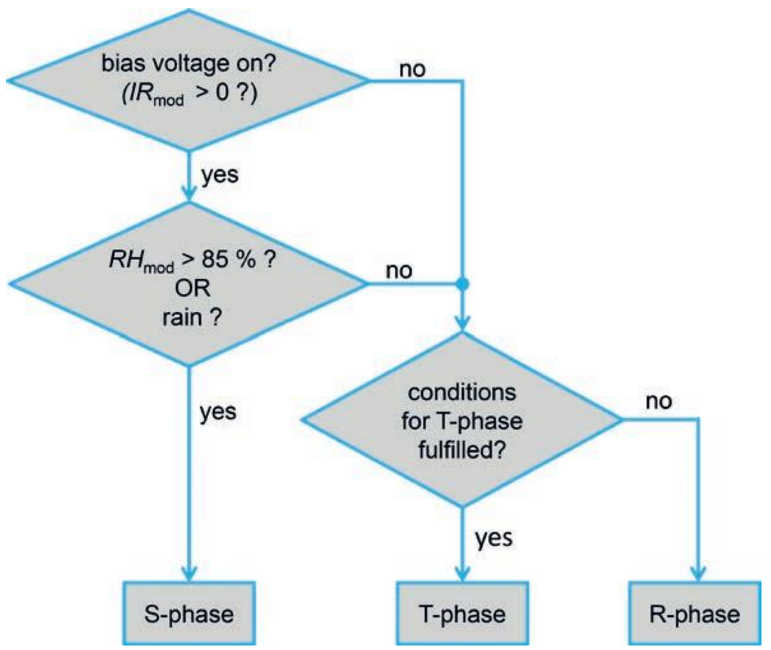

Figure 7. Phase-assignment process for classifying the environmental data, carried out at every time step of the simulation. (Adapted from Taubitz et al. [15].)

individual time step of the simulation; this assignment process is illustrated in Fig. 7.

A time step is assigned to the S phase if the bias voltage is present ($IR_{mod} > 0$) and the module glass is grounded ($RH_{mod} > 85\%$ [19] or rain event). If these conditions are not met, the shunting process is considered to have finished, and the time step is assigned to either the T phase or the R phase. For a time step to be assigned to the T phase, then: 1) the cell type has to exhibit this phase at the current R_{sh} value [14]; 2) the former time step has to be assigned to an S or T phase; and 3) in the case of a preceding T phase, the time elapsed since the beginning of the T phase is not longer than the duration of the T phase.

c) R_{sh} simulation

To describe the R_{sh} progression for the S and R phases, exponential functions were chosen, while for the T phase a polynomial was used [15]. The functions contain fixed and T_{mod}-dependent parameters that have to be determined for the specific module type during the investigation of the R_{sh} kinetics in laboratory experiments [13–15]. Finally the R_{sh} progression is computed for each time step using the experimentally determined parameters of the R_{sh} kinetics, T_{mod} and the classification of the time step.

Model validation

To validate and improve the PID-s model, the R_{sh} progression of framed mini-modules fielded in Thalheim, Germany, at a bias voltage of –1kV was measured and compared with simulation results. A detailed description of the experimental set-up can be found elsewhere [15].

As an example, a comparison between R_{sh} measurements and calculations is shown in Fig. 8. Two one-cell mini-modules, one prone to PID-s (sample type B) and one with APT (sample type A), were investigated. Because of this simple set-up, it is only possible to determine the R_{sh} value without illumination; the periodical measurements are therefore performed at night. The measured night-time R_{sh} values for sample types A and B are shown in Fig. 8 as green and red lines respectively. In addition, simulation results employing meteorological data collected during the time of field exposure are shown for sample types A (dashed green line) and B (dashed red line). Different sets of parameters for the R_{sh} kinetics of sample types A and B were used in the simulation; these were determined using replicas of those sample types in the lab. The T_{mod} used was measured, and the meteorological data were collected in one-minute time intervals.

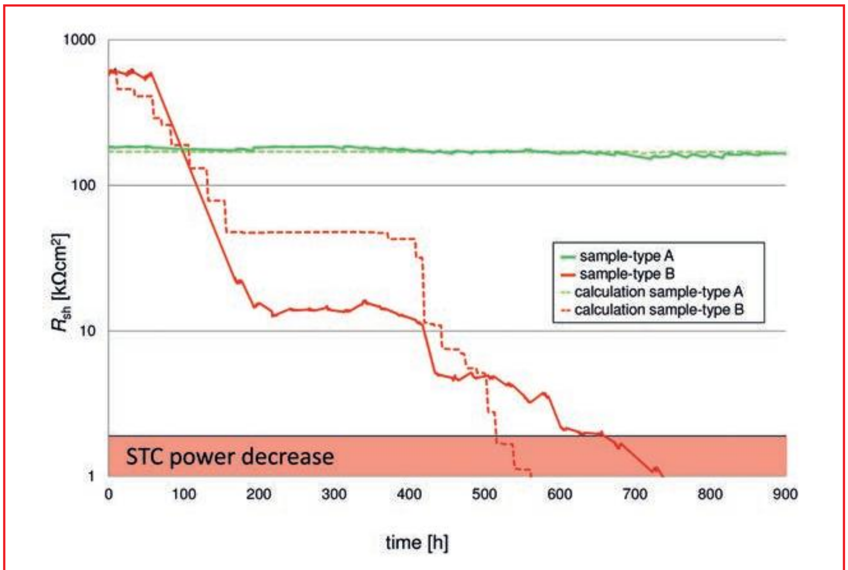

Figure 8. Night-time measurements of R_{sh} over time for two fielded mini-modules, one with APT (sample type A) and one prone to PID-s (sample type B). The corresponding R_{sh} model calculations are also shown (dashed lines).

The first thing to note is that the measurements of the two mini-modules indicate different initial R_{sh} values: whereas for sample type B the intrinsic R_{sh} is about 700kΩcm², the value for sample type A is 200kΩcm². This difference is due to variations in cell production and does not affect the R_{sh} kinetics caused by PID-s. After 900 hours' field exposure with a daytime bias voltage of –1kV, the sample type A mini-module demonstrates only small changes in the R_{sh} value, revealing no significant impact on the module performance due to PID-s. In contrast, the module of sample type B exhibits a significant decrease in R_{sh}, dropping to a value below that of the onset of the decrease in STC power.

A comparison between measurements and model calculations reveals good qualitative agreement. As predicted by the calculation for sample type A, the PID-s stress does not have a significant effect on the R_{sh} value. For PID-s-prone sample type B, the calculation predicts a rapid decrease in R_{sh}, which is in good agreement with the observed decrease. Nevertheless, there are differences between the model results and the experimental data of the visible progression of R_{sh} for sample type B; these deviations are currently being investigated in detail in order to improve the model and its predictions.

Summary and conclusion

PID-s is one of the most severe forms of PID; in contrast to other types of degradation, the resulting loss of power and energy yield can be very high. A negative potential of p-type solar cells with respect to grounded frames/mounting causes PID-s. Although this negative potential can be completely avoided at the system level, this is not the case for a large number of modern PV systems. PV modules that are able to withstand PID-s stress, at least for the duration of their service life, are therefore essential.

To assess if modules fulfil this endurance requirement, laboratory tests are currently recommended that expose the modules to a certain constant level of PID-s stress for a given amount of time. The stress level and duration of constant accelerated stress tests are usually chosen in such a way that the stress of the complete test is equal to the cumulated stress that occurs under non-constant field conditions during the desired service life. This approach is only feasible, however, for degradation mechanisms that are non-reversible in the field, for which non-coherent stress episodes simply sum up to the total stress.

Unlike other degradation mechanisms, PID-s is reversible under field conditions. Actually, the conditions for regeneration from PID-s are always given, provided no PID-s stress is present; this is always the case at night-time and also on dry days. As a consequence, the level of PID-s of a fielded module is the result of an intricate interplay of phases of degradation and regeneration. This behaviour cannot be replicated in laboratory tests with a constant stress level: the currently recommended laboratory tests for PID-s with constant stress levels are therefore not appropriate for assessing the service life duration of a module, and can only be used for differentiating the susceptibility to PID-s stress and for monitoring the stability of production processes.

"By the use of Anti-PID Technology, Hanwha Q CELLS can guarantee an excellent resistance to PID-s during a module service life of 25 years or more."

For monitoring PID-s resistance of its products on a weekly basis, Hanwha Q CELLS (HQC) uses tests for PID-s with constant stress in accordance with the draft for IEC PID test method 62804. This assures that all products of the Q CELLS brand come with APT. With this technology, Hanwha Q CELLS has implemented a combination of materials and process/design parameters that ensures excellent resistance to PID-s, by considering not only degradation but also the regeneration behaviour regarding PID-s. The expected service life duration with respect to PID-s is assessed by simulating the interplay of degradation and regeneration in non-constant outdoor conditions based on meteorological data. By the use of Anti-PID Technology, Hanwha Q CELLS can guarantee an excellent resistance to PID-s during a module service life of 25 years or more.

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