In-the-field PID related experiences

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ABSTRACT

Potential induced degradation could considerably decrease the performance of photovoltaic systems which operate at high DC voltages. Nonetheless, methodologies for dealing with it in field are not clearly yet defined. This work explains the kinetics of this phenomenon in the field and presents an assessment of its occurrence, detection and prediction in real PV installations. Measurements of the instantaneous operating voltages of the photovoltaic module as a verification routine and predictive maintenance is proposed here as a reasonable and most accurate way of analyzing the actual power losses of the photovoltaic system related to this kind of degradation, as well as detecting and predicting it. Potential induced degradation prevention and recovery have also been carried out by the application of reverse voltage during the night, showing the validity of this technique. A literature review for the PID dynamics of different kinds of photovoltaic cell technologies and development of PID test methodologies and standards is also presented.

1. Introduction

Potential Induced Degradation (PID) refers to a loss in the PV module efficiency caused by the high potential (voltage to ground) the solar cells are subjected to during their normal operation [1]. In PV arrays consisting of strings of several series-connected modules, the module potential depends on the grounding configuration of the array (floating or grounded on one terminal or in the center), the inverter switching topology and the position of the module. Whatever the case, the potential is maximum at the terminals (poles) of the string.

The potential gives rise to leakage currents (LC) that flow to earth from the cells through the module insulation, package, frame grounding points and mechanical support. In turn, the LC leads to the accumulation of a charge trapped on the active layer. Cells with a positive potential are affected by a negative charge, which is mainly made up of electrons; while cells with a negative potential are affected by a positive charge, which is mainly made up of Na^+ ions –for standard p-based cells– always present on the soda-lime glass front cover of the module [2,3] and the composition of the anti-reflective coating (ARC). This is exactly the case in standard c-Si modules located at the negative pole of floating voltage arrays, which predominates in current PV-plant market. These ions, helped by a particular kind of crystallographic defect known as stacking faults (SF), are able to shunt the p-n junction of the cell that has been subject to PID formation. The process is particularly significant in the early morning when the front glass is covered with dew, which increases the conductivity of the LC path. Later, irradiance makes dew evaporate, thus decreasing conductivity and causing the ions to recover their equilibrium positions. So PID recovery takes place aided by the increase in temperature and irradiance. The final in-the-field occurrence of PID depends on the balance between PID formation and recovery forces, which depends not only on the characteristics of the PV module but also on the climatic conditions of the location.

Current PID-related test standards address the PID formation but not the PID recovery processes, so modules that have failed in these tests might not necessarily develop PID in the field. Hence the occurrence of PID in the field is an open question as is the need to implement counteractive measures (PV system grounding or/and reverse polarization during the night). An appealing possibility consists of being diligent with periodic predictive maintenance. *"c-Si PID degradation is generally reversible and actions can be taken post-operation. It usually makes more economic sense to use yearly maintenance measurements to detect the existence or absence of PID and then take action only if necessary"* [4]. This opinion is in agreement with our experience. Although feasible PID detection means that routine maintenance practices are necessary, implementing the surveillance allows the PID to be detected early and, if necessary, to adopt appropriate measures before irreversible degradation sets in, due to electrochemical corrosion, takes place.

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Our work only focuses on early PID detection for c-Si conventional modules because this technology dominates the PV market with around 90% share worldwide [5–8]. Different alternatives for in-the-field PID observation in real PV plants were analyzed and it was found that the contrast between the instantaneous operating voltages of the modules at the extremes of the string (positive and negative poles) is more representative to detect PID than other electrical parameters. The procedure is easy to implement in standard predictive maintenance and routine monitoring procedures and it allows not only the detection of PID but also the observation of PID time evolution which provides a way of anticipating the occurrence of PID. The trick is to install module specimens with previous artificially induced PID at the negative pole of a representative number of PV strings. Then, the improvement in PID on these modules (that is, the instantaneous operating voltage of the modules concerned increases) is interpreted as the mechanisms of PID recovery dominating those related to PID formation under the specific climatic conditions of the location and, consequently, the occurrence of future PID is excluded. The opposite is also true: a worsening PID indicated by a progressive decrease in the instantaneous operating voltage is taken as a sign that PID is likely to occur.

2. PID review

Potential was identified as a stress factor in 1978 for inclusion in the qualification tests by the Jet Propulsion Laboratory [9]. However, a test for measuring the durability of the continuous system bias was not included in the qualification standards at that time as it was deemed too stressful [10]. Degradation mechanisms resulting from the stress exerted by system bias voltage depends on the particular module technology. Electrochemical corrosion of transparent conductive oxide (TCO) related to negative potential was described in 1989 [11]. It is associated with Na^+ migration and the presence of moisture (from the extremities of the modules) accelerated as the trapped water vapor increases the electrical conductivity and the LC [3]. In order to avoid this phenomenon, thin-film manufacturers normally produce unframed modules to maximize the resistance of the LC path between the cells and the ground. Furthermore, manufacturers are very likely to require the grounding of the negative terminal of the PV arrays to fully avoid negative potential in the cells.

Another degradation mechanism, this time associated to positive potential, is the surface polarization effect that affects c-Si inter-digitated back-contact solar cells (IBC). First described in 2005 [12], this effect consists of the accumulation of negative charge on the surface of the ARC which attracts positively charged light-generated holes to the front where they recombine with n-type silicon electrons. In other words, this effect increases the surface-recombination rate. Interestingly, the surface polarization effect is found to be reversible and it is avoidable by grounding the positive terminal of the PV arrays, which imposes negative potential to all the cells. Later studies into PID in IBC cells have confirmed the relation between this process and the increased surface recombination, which is attributed to a degradation of the front passivation layer due to ion drift induced damage of the dielectric/Si interface [13].

The term "PID" was introduced in 2010 [14] in a paper dealing with the degradation observed in standard –front and rear contact– p-type c-Si technology. Degradation appears to be associated with negative potential which give rise to cell shunting since both the shunt resistance and the fill factor decrease, which speculatively suggested the incorporation of deleterious ions in the active layer of the cell [15]. That was later confirmed when observing, first, that cell-shunted regions show an accumulation of Na^+ and other alkali metals on the surface and within the SiN_x ARC layer [16,17] and, second, that shunts are also correlated with a kind of crystallographic defect called Stacking Faults (SF) which provide diffusion channels for Na^+ across the p-n junction [18,19]. The experimental findings were later corroborated and explained through computational simulations [20]: it is energetically favorable for Na^+ to segregate at the SF. Although a large electrical potential is required to transport Na atoms from the source (which could be the front cover glass or the SiN_x ARC) to the $SiN_x/SiO_x/Si$ interface, they then spontaneously diffuse into the SF creating an electrically conductive 2D layer and causing p-n junction short-circuiting inside the PV cell.

PID has also been detected in standard n-type c-Si technology and it is suspected that the effect in this case is not brought about by Na^+ diffusion, as in p-type solar cells, but by positive charges –mostly K^+ centers– trapped in the SiN_x layer. The trapped charges lead to an increasing concentration of the minority carrier in the p-layer which consequently increases the charge recombination rate on the surface [21].

In common with the occurrence of PID in p-type and n-type PV cells is that both effects, Na^+ diffusion and K^+ center trapping, are reversible and avoidable by grounding the negative terminal of the PV arrays, which automatically imposes positive potential on all of the cells. A comprehensive review of the underlying mechanisms of PID has recently been published [1].

PID due to shunting and/or polarization can be reversed by the natural tendency of the dislocated ions to recover their equilibrium positions once the LC causing the PID ceases. This natural tendency can be observed when a degraded PV module is stored at room temperature and in the dark as P_{STC} recovers slightly over time. This recovery can be accelerated by heat since it increases the mobility of the ion [14,22,23]; as does exposure to sunlight, which is probably related to the increase in ARC conductivity during illumination [24].

2.1. Kinetic of the PID in the field

As regards the field, floating PV arrays are usually preferred in comparison to grounded ones for reasons of electrical safety: floating PV arrays are intrinsically safe should there be a first ground-fault because the corresponding default current is strongly limited by the isolation resistance of the PV array. Moreover, floating PV arrays minimize the system voltage to ground and can be connected to the distribution grid by means of transformerless inverters, which is why most standard (front and back contact) c-Si technology PV arrays are just floating ones. Furthermore, PV module frames are always grounded as protection against indirect contacts and lightning.

PID proceeds as a dynamic process in these standard c-Si floating PV arrays, somewhat as a trial of strength between PID formation and PID recovery: LC between cells at negative potential and ground, causing the displacement of positive ions, depends on the voltage applied and the resistance of the path between the affected cells and the grounded frame. The surface of the front glass is the key pathway under outdoor operating conditions [25,26]. Early in the morning the glass is covered with dew, which increases the conductivity significantly, while irradiance gives rise to PV system open-circuit/operating voltage. Under these conditions, which also happen on rainy days, the path resistance is mainly due to the bulk of the front glass and the encapsulation, and reaches the minimum value. Hence, LC increases and PID tends to form. Interestingly, surface soiling also has a role: it acts as a storage matrix for humidity, like a sponge, and extends the surface grounding period with high LC [27]. As the day goes on, irradiance makes the dew evaporate, the LC path resistance takes place all over the surface of the glass and the value of this resistance increases significantly (the typical distance from the frame to the border cells is a few cm, i.e. several times larger than the thickness of the glass), leading to a halt in LC. Then, PID recovery takes place helped by PV module operating temperature and irradiance. During the night, the PV voltage is null so that PID also tends to recover even in case of dew. PID recovery during the day at elevated temperatures is typically more relevant than recovery during the night at low temperatures [28]. However, PID recovery during the night can be accelerated by reverse polarity, i.e. applying a positive voltage between the PV modules and the ground. This is the fundament