COLEÇÃO DESAFIOS DAS ENGENHARIAS:

ENGENHARIA ELÉTRICA 2

JOÃO DALLAMUTA
HENRIQUE AJUZ HOLZMANN
(ORGANIZADORES)

Atena Editora
Ano 2021

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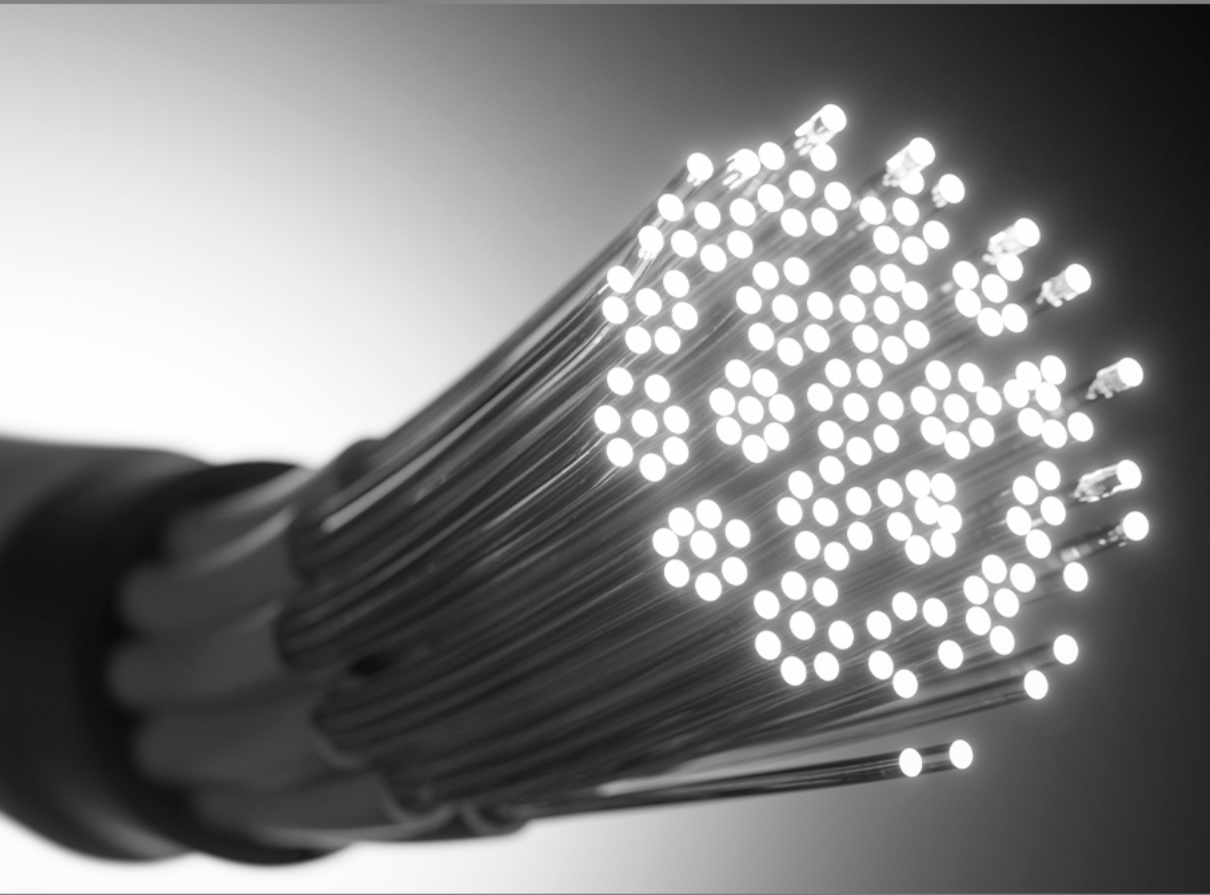

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Dados Internacionais de Catalogação na Publicação (CIP)

C691 Coleção desafios das engenharias: engenharia elétrica 2 / Organizadores João Dallamuta, Henrique Ajuz Holzmann. – Ponta Grossa - PR: Atena, 2021.

Formato: PDF
Requisitos de sistema: Adobe Acrobat Reader
Modo de acesso: World Wide Web
Inclui bibliografia
ISBN 978-65-5983-556-0
DOI: https://doi.org/10.22533/at.ed.560211910

1. Engenharia elétrica. I. Dallamuta, João (Organizador). II. Holzmann, Henrique Ajuz (Organizador). III. Título.

CDD 621.3

Elaborado por Bibliotecária Janaina Ramos – CRB-8/9166

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Ponta Grossa – Paraná – Brasil
Telefone: +55 (42) 3323-5493
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APRESENTAÇÃO

A engenharia elétrica tornou-se uma profissão há cerca de 130 anos, com o início da distribuição de eletricidade em caráter comercial e com a difusão acelerada do telégrafo em escala global no final do século XIX.

Na primeira metade do século XX a difusão da telefonia e da radiodifusão além do crescimento vigoroso dos sistemas elétricos de produção, transmissão e distribuição de eletricidade, deu os contornos definitivos para a carreira de engenheiro eletricista que na segunda metade do século, com a difusão dos semicondutores e da computação gerou variações de ênfase de formação como engenheiros eletrônicos, de telecomunicações, de controle e automação ou de computação.

Produzir conhecimento em engenharia elétrica é portando pesquisar em uma gama enorme de áreas, subáreas e abordagens de uma engenharia que é onipresente em praticamente todos os campos da ciência e tecnologia.

Neste livro temos uma diversidade de temas, níveis de profundidade e abordagens de pesquisa, envolvendo aspectos técnicos e científicos. Aos autores e editores, agradecemos pela confiança e espirito de parceria.

João Dallamuta

Henrique Ajuz Holzmann

SUMÁRIO

CAPÍTULO 8

DEGRADAÇÃO POR POTENCIAL INDUZIDO (PID): REVISÃO

Data de aceite: 01/10/2021

Data de submissão: 20/08/2021

Hellen Ferreira Barreto Miranda
Instituto Federal Fluminense – campus Campos Centro
Campos dos Goytacazes – RJ
http://lattes.cnpq.br/3244001760009862

Luan Peixoto da Costa
Instituto Federal Fluminense – campus Campos Centro
Campos dos Goytacazes – RJ
http://lattes.cnpq.br/5624490921923509

Stefhany Oliveira Soares
Instituto Federal Fluminense – campus Campos Centro
Campos dos Goytacazes – RJ
http://lattes.cnpq.br/1582723630335668

Jonathan Velasco da Silva
Instituto Federal Fluminense – campus Campos Centro
Campos dos Goytacazes – RJ
http://lattes.cnpq.br/9478738230520097

RESUMO: A degradação induzida por potencial (PID) é uma problemática que nos últimos anos tem sido foco de pesquisas e estudos sobre o desempenho do módulo fotovoltaico (PV) em condições de campo, tendo em vista as consequências ocasionadas por esta degradação. Mesmo com um extenso material nessa área, a compreensão sobre o fenômeno PID ainda é incompleta, mas deve-se levar em consideração que a diversidade tecnológica e ambiental são fatores que implicam nas técnicas de reversão. Este artigo visa realizar uma revisão crítica a fim de fornecer uma visão geral e ampla da literatura disponível para promover a compreensão do estado atual da pesquisa PID. O papel consiste em apresentar as definições do mecanismo PID embasadas por estudiosos e pesquisadores bem como a influência da temperatura, umidade e da tensão na progressão do PID e as metodologias de detecção e reversão e as medidas preventivas em módulos PV c-Si.

PALAVRAS-CHAVE: Detecção, revisão literária, PID, fotovoltaico, reversão.

POTENTIAL-INDUCED DEGRADATION (PID): REVIEW

ABSTRACT: Potential induced degradation (PID) is a problem that in recent years has been the focus of research and studies on the performance of the photovoltaic module (PV) under field conditions, in view of the consequences caused by this degradation. Even with extensive material, the understanding of the PID phenomenon is still incomplete, but it must be taken into account that technological and environmental diversity are factors that imply in reversal techniques. This article aims to conduct a critical review in order to provide an overview and broad view of the literature available to promote understanding of the current state of PID research. The role is to present the definitions of the PID mechanism supported by scholars and researchers as well as the influence of temperature, humidity and tension on the progression of the PID and the

detection and reversal methodologies and preventive measures in PV c-Si modules.

KEYWORDS: Detection, literary review, PID, photovoltaic, reversal.

1 I INTRODUCTION

The relevance of photovoltaic generation (PV) worldwide, along with the growing energy demand, has led to greater participation of this source in the energy matrices of the countries. The wide use of photovoltaic systems has led to greater investment in research and innovation of this energy source, seeking to optimise cell efficiency, reduce production costs, the development and discovery of new materials for photovoltaic modules. Another aspect that has been the subject of studies is the degradation of photovoltaic modules by several factors, compromising performance, reliability, as well as service life. The degradation is related to several factors, being able to originate in the manufacturing process of the modules and also the exposure conditions, due to the incidence of the radiation itself, the ultraviolet radiation, temperature and humidity since they are exposed to different environmental and climatic conditions.

The most common problems in modules with crystalline silicon solar cells are interrupted interconnections, broken cells, corrosion, delamination of the encapsulant, discoloration of the encapsulant, broken glass, bypass diode and weld tape failure, as well as degradation induced by electrical potential, hot spots and bubble formation on the backsheet, among others (NDIAYE, 2013).

A degraded photovoltaic module can continue to perform its main function, which is to generate electricity from sunlight, even if its use is not as efficient as initially was. However, the degraded state of the module can be more problematic when the degradation exceeds a critical point (CHARKI,2013). It is important to note that manufacturers consider a PV module to be degraded when its energy reaches a level below 80% of its initial energy.

Among the many problems affecting the performance of the PV module, potential-induced degradation (PID) has attracted the most interest in recent years, more precisely from 2010, this is due to the fact that PID occurs frequently in photovoltaic systems and solar parks, where the voltage of strings are higher.

The PID is related to the difference in potential of the module in relation to earth combined with high humidity and high temperatures, causing loss in power due to unwanted leakage current to the ground, since this decreases the efficiency of the cells (FIGUEIREDO, 2015).

Although most studies on potential-induced degradation are based on p-type crystalline silicon photovoltaic modules, recent research seeks to include photovoltaic modules composed of other cellular materials, as perovskite, thin film solar cells of Indium Gallium Copper Disselenete (CIGS) or whose technology is PERC. Thus, this article aims to carry out a bibliographic review on potential-induced degradation in c-Si photovoltaic modules.

2 | ELUCIDATION OF PID IN PV MODULES

The low maintenance cost, the non-emission of pollutant gases and the lifetime of more than 25 years are fundamental requirements for the implementation of photovoltaic technology in power plants. However, over this time, some problems begin to arise, whether with the inverters installed, whose average operating time is 10 years, whether by other decomposition mechanisms that decrease the efficiency of solar generation or contribute to the destruction of solar cells. In 2010, potential induced degradation (PID) of crystalline silicon solar cells was considered one of the major degradation mechanisms (PINGEL, 2010), this is due to the fact that PID causes a serious initial energy loss, negatively impacting the performance and reliability of the PV module under field conditions (WANG et al, 2016) . Thus, several global PV research institutes have leaned towards PID-related research in photovoltaic modules, in which the term PID was coined by Pingel et al, basing a large amount of work in order to solve and verify its causes (HYLSKÝ et al, 2018).

To achieve greater solar power generation, in the photovoltaic systems connected to the grid, PV modules are connected in series to generate a high output voltage, while the module frame is grounded for safety reasons (Fig.1) in the meantime solar panels may be exposed to high voltage between the solar cell and the module structure. This potential difference causes leakage currents to travel between the metallic structure of the module to the solar cells, or vice versa, depending on the position of the module in the string, through the front glass and the encapsulation. The effect is stronger the closer the module is to the negative pole of the photovoltaic system.

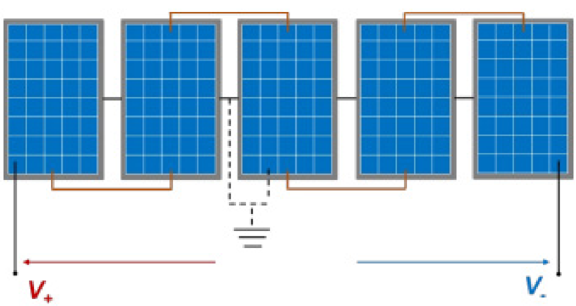

Figure 1. A simplified schematic diagram of a PV system with a floating potential.

Fonte: LUO, 2016.

Studies on the degradation mechanisms caused by high voltages and leakage currents of photovoltaic modules were initiated in 1985 by the Jet Propulsion Laboratory (JPL), more precisely in crystalline silicon (c-Si) and amorphous silicon (a-Si) modules thin film, these were performed outdoors and involved electrochemical and galvanic corrosion, electromigration, and heating by hot spots. Due to the different environmental and climate conditions and the diversity of solar panel specifications and technologies, there is also emphasis on research to mitigate the effects and causes of PID and to clarify the relative sensitivities of various commercial absorbers today (HYLSKÝ et al, 2018). Since there is no constant pattern for the emergence of the effects of degradation on the module.

The conditions necessary for the occurrence of PID involve (i) environmental factors as well as factors on (ii) system, (iii) module and (iv) cell level (PINGEL et al, 2010). While the environment is set for each individual installation, it is possible to prevent the PID by properly controlling only one of the factors (ii), (iii) or (iv) (SCHÜTZE et al, 2011). In this way, all these factors will be addressed below.

Humidity and temperature negatively affect the performance of the photovoltaic system. In humid climate, the unwanted leakage current decreases the cell performance (SCHWARK et al, 2013), since the high humidity and high temperature facilitate the reaction and diffusion of the metal ions in the encapsulated glass, since this moisture forms a film on the glass, which becomes electrically conductive and therefore the PID effect occurs more easily.

One of the most favorable circumstances for the occurrence of PID is the sunrise of sunny days, period of occurrence of dew, due to the formation of droplets forming a thin layer of water on the glass that causes the increase of humidity. This increase causes the resistivity to decrease and facilitates current leakage through the glass. Throughout the day the humidity decreases due to the temperature rise, thus causing a linearly decreasing leakage and the PID effect does not become relevant during the generation process. It should be noted that the moisture in the encapsulation causes a constant current for a while. At the end of the day this current reaches almost zero, but after this time, the temperature decreases and the PV module becomes moist again (HOFFMANN, 2014).

It is important to note that just as high temperatures cause an increase in the degrading effects caused by PID, high temperatures are used during the regeneration processes of modules against PID. As it is not possible to change the environmental conditions in which the photovoltaic plants are located, the research is based on examining and addressing the PID through the system and the photovoltaic modules.

Regarding the system level, a difference in potential and signal from the module are the aspects that provide the most significant impacts. These in turn depend both on the position of the module in the array, the topology of the grounding, the extent of the photovoltaic arrangement and the type of inverter connected to the system.

The choice of the protective glass and the encapsulating material have been shown to influence the occurrence of PID, since they are in direct contact with the cells. The various types of encapsulation significantly affect PID, modules using EVA (ethylene vinyl acetate) are more prone to PID occurrence, since all different substitutes were able to prevent. Studies point out that acetic acid contained in EVA together with moisture may be responsible for dissolving metal ions at the glass interface (SCHWARK et al, 2013).

Base resistivity, emitter sheet strength and anti-reflective coating (ARC) properties are parameters that influence the sensitivity of the PID effect at the cell level. The anti-reflective coating has the function of increasing light capture, hence the module power conversion is higher. However, the properties used in the anti-reflective coating of the solar cell are factors that significantly affect the effect due to its dependence on the silicon nitride ARC (Sin) (NAGEL, 2011).

Another factor contributing to the emergence of the PID effect is the accumulation of ions in the ARC, since this leads to the formation of an electric field in this region, causing an antipassivation effect, increasing the recombination near the surface of the photovoltaic cell, in addition to acting as an undesirable path to escape currents (LAUSCH et al, 2014).

3 I DETECTION AND REVERSAL TECHNIQUES

In order to prevent or mitigate PID effects, it is critical that its detection is done in a rapidly and assertively manner, because the degradation mechanisms can result in high yield losses of 20%, or more in cells that aren't PID resistance. To prevent degradation, all the components of the module such as encapsulant and glass should be resistant to PID, the solar cell also must be resistant and to achieve this, a possibility is to optimize the anti-reflexive coating (KAPUR, 2015).

The phenomenon occurs most frequently in photovoltaic modules that are closer to the negative pole, when C-Si type p cells are used and in high-voltage array systems (KAPUR, 2015) and various research shows that the type of encapsulant used in the module can directly affect the effect (HOFFMANN, 2014). High yield losses may be an indication of degradation by the PID effect (HACKE et al, 2011).

PID can be detected in a number of ways, with thermographic imaging (CÂMARA, 2019), electroluminescence imaging, open circuit voltage measurement, plotting the I-V curves of the modules (ISLAM, 2018), shunt resistance measurement (SCHWARK et al, 2013), and the use of the mass spectrometer to observe the sodium migration within the module (ISLAM, 2018).

Electroluminescence imaging (Fig. 2) has gained a growing interest due to its quick resolved defect detection possibilities such as, detection of recombination, resistive and optical losses of the modules, low diffusion lengths, high series resistance and shunts. It has been observed from the electroluminescence imaging of the on-site degraded photovoltaic module that a performance degradation happens due to different types of cell defects, such as, localized shunting, cracks and front contact grid interruptions (NAUMANN et al, 2013). To capture the electroluminescence images the module is operated as a light emitting diode, and due to recombination effects the emitted radiation can be detected with a camera that photographs the emitted photons. In the images the damaged areas have less or no brightness, while those without defects have a shine (SCHWARK et al, 2013). Modules affected by PID develop a lower operating voltage compared to other modules in the array, and these voltage differences can cause hot spots. This way the thermographic imaging assists in the detection of PID as the hot spots indicate the temperature increase of the affected cells (HACKE et al, 2011). As we can see in the the image (Fig. 3), the cells closer to the frame show hotter spots than the rest of the cell (CÂMARA, 2019).

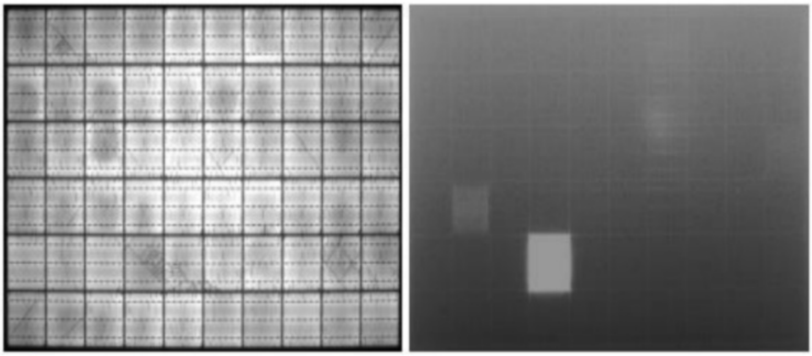

Figure 2. The left image is of the module before degradation and the right image after degradation.

Fonte: (HOFFMANN, 2014).

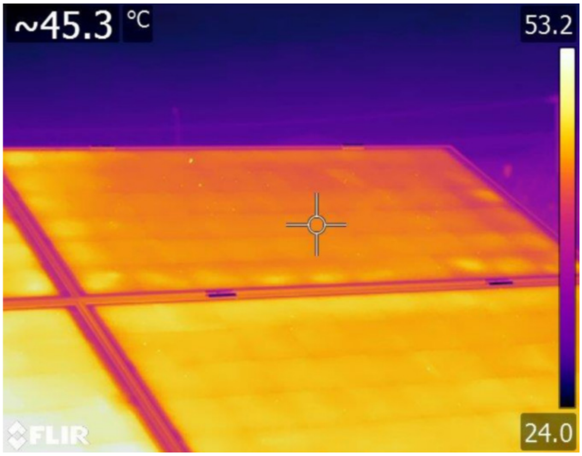

Figure 3. Thermographic image of a module with PID traces.

Fonte: (OH, 2015).

When comparing electroluminescence images and electroluminescence images, there is a slight correlation between the regions with the highest temperature and those with the lowest brightness (PINGEL, 2012).

The shunt resistance (Rsh) of the modules who has the PID resistance encapsulant proved to be approximately steady, while the ones that aren't resistant to PID had shown a decrease in the shunt resistance (ISLAM, 2018). Such resistance is also affected by the different voltages of the degraded modules (PINGEL, 2012).

As the migration of sodium from the anti-reflective coating to the solar cell has been observed after PID tests, the use of the mass spectrometer will observe its accumulation in both the encapsulant and the solar cell (NAUMANN et al, 2013). The module parameters as maximum power point, open circuit voltage, short circuit current, FF (fill factor), and leakage current are drastically reduced as both decrease when the module is affect by PID (HACKE et al, 2011).

The I-V curve (Fig.4) of the affected modules show that the maximum voltage is not the same when compared with the modules that did not suffer from the effect (PINGEL, 2012).

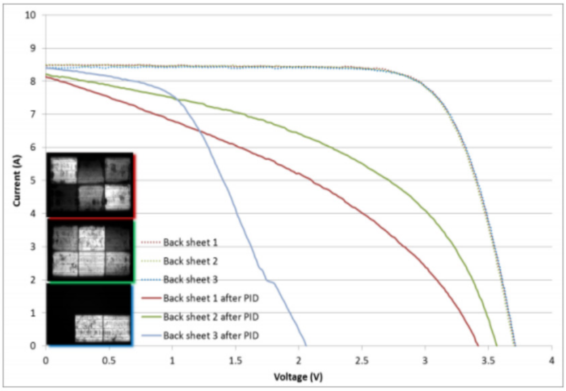

Figure 4. Curves of modules with different back sheets before and after 24h PID test.

Fonte: (KOCH et al, 2012).

Photovoltaic modules shall always be connected in series, taking into account the technical characteristics of the inverters used. The effect that this event brings to large projects is the high voltage created, causing problems detected at both the system level, the panel level and the cell level (HYLSKÝ et al, 2018). These effects are the major causes that can be minimized or even reversible. Climatic factors such as temperature are allies against PID, it has been shown that panels stored at temperature around 100 degrees Celsius for 10 hours lead to a recovery of close to 100% (Fig. 5) (PINGEL, 2012).

In 2010, the most important factor for the appearance of PID was characterized by the large potential difference between cell and soil at the level of the system. For this situation, a reverse potential must be acting in order to reduce this DDP (Potential Difference) (PINGEL, 2010), a system contained in the inverter referring to the string of solar plates called PID doctors can be used for this type of solution. This adaptation will reverse the polarity referring to the polarity of energy generation, causing the reduction of the generated potential, without this electric field, the sodium ions that were previously deposited in the stacking failures will be removed (HYLSKÝ et al, 2018). Field research for module regeneration shows reversals performed in two distinct strings. In one string a grounding kit was used, in another, was used a SMA PV Offset Box that applies a positive potential in the panels. In both cases, significant recovery was demonstrated over time (Fig. 6) (OH, 2015).

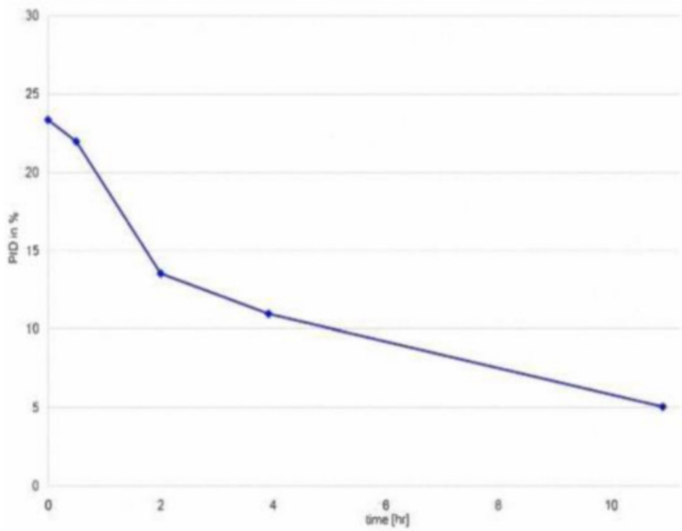

Figure 5. PID recovery using a temperature of ~100°C.

Fonte: (PINGEL, 2010).

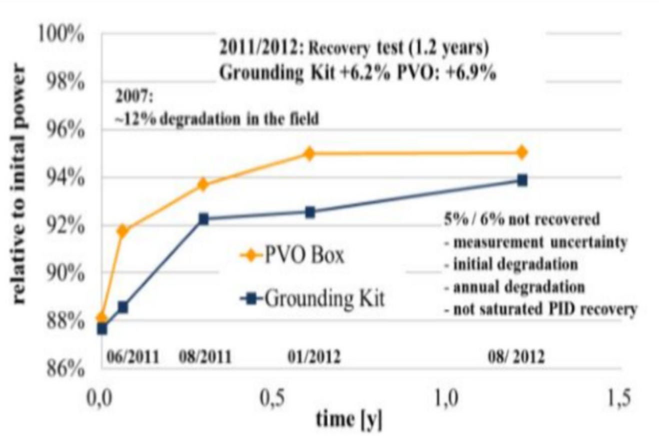

Figure 6. Relative recovery of time degraded panels versus PVO Box and PV-Grounding.

Fonte: (SUGIMURA, 1999).

Reverse voltage system techniques have PV recovery rates (80% - 96%) (CÂMARA, 2019). It should be noted that the junction between reverse voltage, along with application of a temperature higher than the ambient temperature, can recover the maximum power of a cell by up to 96% considering an irradiance of 1000 W/m² (HACKE et al, 2011). Although temperature is an important catalyst in panel regeneration, it is evident that very high temperatures can affect module materials, impairing their long-term performance (PINGEL, 2010).

Regarding the panel, in the manufacturing some presente characteristics of the materials that compose it can be modified in order to minimize the intensity of leakage currents that can n case they lead the cells suffer the PID process. In order to prevent the entry of sodium ions into the cell and encapsulationççof the panel, a layer of phosphorus silicate (PSG) was used in the glass. This layer was elaborated in the solar cell emitter diffusion process (HYLSKÝ et al, 2018), and the goal was not to reduce the efficiency of the photovoltaic cell, parameters such as short circuit current and open circuit voltage, maintaining resistive properties against the PID, preventing the penetration of sodium on the surface of the silicon. The technique was achieved by making necessary modifications to the dissemination process (HYLSKÝ et al, 2018). The transport of sodium from the glass to the cell is one of the major factors for the formation of PID, however, it is not yet known for sure how much sodium is needed for the formation of PID (OH, 2015). Using a glass that does not have sodium in its composition effectively protects the cell against PID (KOCH et al, 2012). Two glasses with different sodium levels were tested, borosilicate Glass with 6.5% sodium by weight and soda-Lime Glass with 16% sodium by weight. It was observed in the PID tester that the glass with a lower sodium composition has a higher resistance against PID after 100 hours of testing, while the soda-Lime Glass in 24 hours already presented accumulation of sodium deviation, indicating that the sodium in the glass is critical for PID (HACKE et al, 2011).

Changes in composite materials in the separation of photovoltaic panel materials demonstrate improvements in the PID process. In (HYLSKÝ et al, 2018) it proves that lamination films intended to prevent thermal and electrical isolation of the cell that directly affects PID degradation. Ethylene Vinyl Acetate (EVA), which is widely used today in the manufacture of panels, can be replaced by other materials that have different characteristics from EVA, such as conductivity, decreasing the migration of sodium ions, slowing the emergence of PID. The materials can be partially neutralised by ethylene methacrylic copolymer, EVA copolymer or polyolefin elastomer (HYLSKÝ et al, 2018). Power comparison between modules with ionomer and EVA films was diagnosed. Modules with ionomers retain, after 500 hours of exposure to PID, 99% power, while modules with standard EVA film lose almost all power in 24 hours of testing. A PID tester demonstrates in temperature conditions 85°C and 85% relative humidity and no leaf performed at 96 and 192 hours, stating (Fig. 7) that the standard EVA film has low resistance falling to close to 11.5% of its power compared to the ionomer that maintained 98,5% of its power. Through Laser Ablation-Inductively Coupled Plasma Mass Spectrometry, the accumulation of sodium ions can be obtained after the test. The reading demonstrates a high concentration of sodium in the EVA encapsulation and in the cell compared to the ionomer, reporting also that the deposition of sodium ions in the ionomer layer and cell occurs slowly when compared to standard EVA (HOFFMANN, 2014).

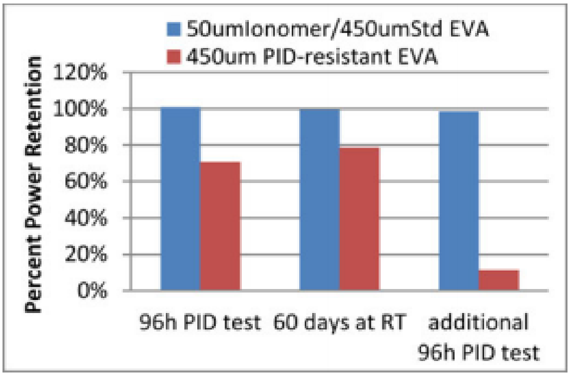

Figure 7. Modules with ionomer and EVA demonstrating the resistance of both films against PID.

Fonte: (KAPUR, 2015).

At the cell level, modifications to the cell structure can decrease PID aggressiveness. In (OH, 2015), it describes the manufacture of two or three anti-reflective coatings to reduce the susceptibility of the PID (KOCH et al, 2012). However, the improvements achieved are too low to be practical PID solutions, and the disadvantages of this modification can considerably affect the efficiency of photovoltaic cells due to the refractive index of these layers. The refractive index of ARC was considered the only parameter capable of preventing the PID effect in PV modules. According to reports by (SCHÜTZE et al, 2011) the PID does not occur if the refractive index of a silicon nitride ARC is 2,2% or more.

4 I CONCLUSION

This article presented a bibliographic review of the Potential Induced Degradation (PID) mechanism that is becoming more relevant with the growth of the photovoltaic system, in which the system tensions are higher. It has been shown that the origin of the PID can be at the cellular, module and system level, as well as the reversal. The solution at the system level is to apply a reverse voltage in order to reduce the DDP between the ground and the system. At the cellular level many parameters influence the stability of the PID, in addition to the resistivity of the base and the resistance of the emitter sheet, the most important parameters were the properties of the anti-reflective coating. Since the changes of this layer can avoid the PID effect. Recently, most of the modules marketed are already manufactured with the PID-free description, showing that the industry has been trying to fix the problem, early in the manufacture of the modules (FIGUEIREDO, 2017). The high temperatures also proved to be an ally to the regeneration of the PV module detected with PID.

It has also been reported on the detection techniques, in which the images obtained through the thermographic technique and electroluminescence and the plotting of the I-V curve, among other methods, are used in several researches, Thermal images are a viable technique to be performed in the field and with great possibilities to infer the existence of PID, being the rapid possibility of detecting problems in one or more modules.

Given these conclusions, it is expected that from this study, the understanding of the current state of research related to PID, other works could be developed to achieve a significant improvement in the effects of the PID and to provide stability of solar panels.

We intend to continue this work by analyzing the methodologies and techniques presented here in photovoltaic modules installed in photovoltaic plants in the region of Campos dos Goytacazes (RJ) and Cabo Frio (RJ) in order to prove the analysis of field studies by other authors.

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