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A review of the different mechanisms of degradation of photovoltaic modules

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ABSTRACT

The lifespan of Photovoltaic (PV) modules is estimated at 20 to 25 years depending on the manufacturer. Obviously, solar modules do not necessarily maintain their initial performance, they can deteriorate or even become faulty when they operate on a real site for prolonged periods. The problems related to the grouping of solar cells (imbalance, hot spot) and which affect the performance of photovoltaic modules as well as the stress factors which are the drivers of degradation are addressed in this article through a bibliographic review.

Key words: photovoltaic, solar energy, degradation

1. INTRODUCTION

Energy from the sun has the advantage of being available worldwide in unlimited quantities and solar cells are one of the main means of recovering this energy since they are able to convert sunlight directly into electricity with almost no generate pollution.

The study of a photovoltaic module means, in particular, the determination of the main parameters of the equation that governs its electrical characteristic. Once its parameters are known, they can easily be used to determine the performance of the photovoltaic module considered.

The performance of PV modules varies with climatic conditions and gradually deteriorates over the years [1-4].

However, the use of photovoltaic conversion, on a large scale, is dependent on certain technical and economic factors. In this case, the photovoltaic generator is the main element in a system. On the one hand, it is the most expensive element of a photovoltaic chain, on the other, the performance of any photovoltaic system depends on the efficiency of the generator (photovoltaic module). Indeed, in any photovoltaic system, the module plays a main role in the energy balance. Therefore, it must be seen more closely in the analysis of the operation of a photovoltaic system **[5]**.

A drop in the efficiency of a PV solar panel throughout its life cycle is not desired, since the capital costs for the system are quite high. PV cells normally have a lifespan of around 25 years, and it takes approximately up to six years [6-8] for a solar PV module to produce an equivalent amount of energy consumed in its manufacturing processes.

An important factor in the performance of photovoltaic technologies has always been their long-term reliability, especially for new emerging technologies. The most important issue in long-term performance evaluations is degradation. Degradation is the result of a gradual loss of power or performance depending on a number of factors such as cell, module or system level degradation. In all cases, the main environmental factors related to the degradation mechanisms are temperature, humidity, dust and ultraviolet rays. All these factors induce significant stress on the lifespan of the modules [9].

The lifetime of a PV module can be defined as a point in time at which the module is no longer acceptable for any reason, whether in terms of safety, appearance, catastrophic event, or when the supplied power falls below an acceptable Osterwald value [10]. This taken into account, the same component can have a different failure criterion according to its role in such or such system. In general, the useful life of a module is the period during which its performance is guaranteed within a given interval. The current consensus is that a PV module is guaranteed for 25 years at 80% of its initial power and 90% after 10 years.
After a theoretical presentation of degradation, this article emphasizes the great diversity of degradation modes that can appear at all levels of a PV system. It also discusses the tools used to highlight system failures.

2. PHOTOVOLTAIC MODULE: AN ELECTRICAL POWER GENERATOR

The elementary photovoltaic cell constitutes a low-power electrical generator with regard to the needs of most domestic or industrial applications. Indeed, an elementary cell of a few tens of square centimeters delivers, at most, a few Watts under a low voltage, in principle, since it is a junction voltage.
These cells are marketed in the form of photovoltaic modules combining, generally in series to raise the voltage, a certain number of elementary cells with identical technology and characteristics [11].
In addition, this series assembly must be protected to make the module suitable for outdoor use. Cells are in fact fragile and corrosion-sensitive objects that should be mechanically protected and sheltered from the rigors of the climate.

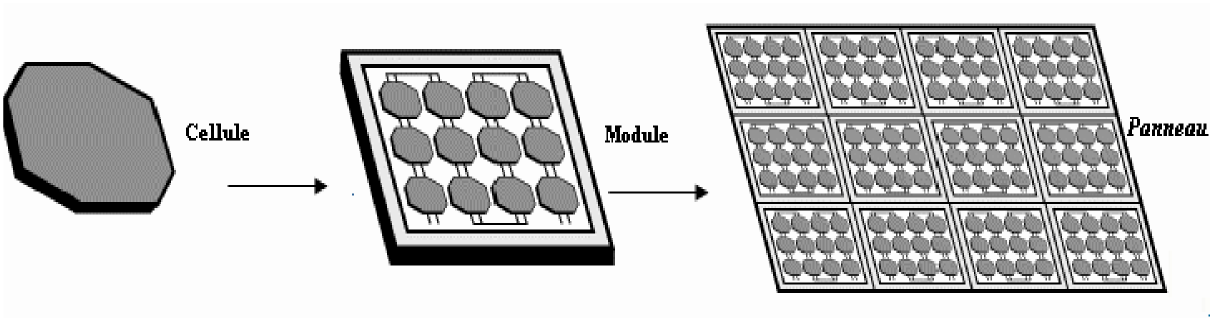

Fig. 1 Association of photovoltaic solar cells

The cells are chained together, then the chains are interconnected to form a matrix. The matrix is encapsulated by hot rolling: the laminates are brought up to temperature and pressed under vacuum. The Ethylene Vinyl Acetate (EVA) film placed between the glass on front of side or the back of side and the cells ensures the cohesion of the whole by cross-linking. Each module is equipped with a junction box containing protection diodes and allowing its electrical connection [12].
The four characteristics that have made EVA a material of choice for encapsulation are its:

- very high electrical resistivity classifying it as a very good electrical insulator;
- relatively low melting and polymerization temperature;
- very low water absorption rate;
- good optical transmission.

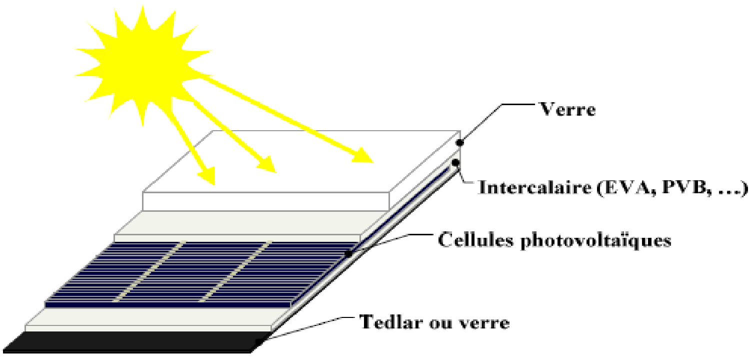

Fig. 2 Components of a crystalline module

The current produced by a PV sensor is therefore much lower than half of the photons arriving on the material because several conditions must be met for the energy of the photon to really translate into current.

The transformation of solar energy into electrical energy is based on the following three mechanisms (fig. 2)
Absorption of incident photons (if the energy of the photon is greater than the gap) by the material constituting the device;
Conversion of photon energy into electrical energy, which corresponds to the creation of electron-hole pairs in the semiconductor material;
Collection of particles generated in the device.
Obviously, photovoltaic modules do not necessarily maintain their initial performance. They can degrade or even fail when operating on-site for extended periods. Several factors can be the cause of such degradation and drops in the performance of photovoltaic modules. A perfect analysis and monitoring of the phenomenon of the degradation of photovoltaic modules requires a complete series of special techniques. The supplier's nameplate does not include any information on long-term degradation. However, the numerous photovoltaic systems that have been in operation for more than 20 years have made it possible to acquire information on the mechanisms of degradation [13-14].

III. NOTION OF DEGRADATION

Degradation is the progressive deterioration of the characteristics of a component or system which may alter its ability to operate within the limits of the acceptability criteria and which is caused by the service conditions. A degrading product becomes pseudo-failing when it reaches a degradation limit threshold. At each instant, the reliability can be estimated as the probability that the degradation measure is smaller than a target degradation value. The degradation model is an effective way to predict reliability when the product degrades. In general, to estimate the reliability of a product by testing, this product is artificially aged in order to reproduce the failure mode or the degradation model.
A product that is subject to the phenomenon of degradation may never lose its main function even if its use is not optimal, we speak of a degraded state. However, this degraded state can become critical for the system when the degradation exceeds a critical degradation threshold. The product is said to be pseudo-failure **[15]**.
During its period of use, the PV module is exposed to various environmental stressors. These are the factors that are responsible for the failures, and in the long term, for the aging of the modules.
The performance of the modules can be degraded due to several factors such as:
• Static and dynamic mechanical loads,
• Thermal cycles,
• Exposure to radiation,
• Humidity,
• Hail impact (grains of sand),
• Accumulation of dust,
• Partial concealment…

IV. THE DIFFERENT MODES OF DEGRADATION

The stress factors described above are the drivers of module degradation. When a degradation appears, it is perceptible by its effect (loss of performance, modification of the visual aspect, etc.). Often, degradation factors are linked to the action of atmospheric agents with, possibly, manufacturing defects **[14]**.
The major defects most observed after the aging of solar modules exposed to different environments are:
• Discoloration of EVA
• Delamination
• Formation of hot spots (or hot-spot)
• Cell cracking

1. Discoloration of EVA

One of the most common degradation mechanisms for photovoltaic modules is discoloration of EVA or other encapsulation materials. This type of degradation is mainly considered an aesthetic problem **[16]**.
The absorption of Ultraviolet (UV) rays by the Eva layer often leads to a reduction in the service life of the module encapsulation materials (Fig. 3). In particular, the browning of the EVA layer, accompanied by an accumulation of acetic acid, causes a gradual reduction in the energy production of certain modules **[17]**.
Often, this change in color of the EVA is noticed after a few years of exposure (yellowish then brown colouring). Oreski and Wallner **[18]**, determined that the cause of this defect in the encapsulant is ultraviolet radiation and

exposure to water combined with temperatures above 50°C. These factors together cause a change in the chemical structure of the polymer.

E.Keplani **[19]**, made a study on the degradation of PV modules during a few years of operation. During this study he detected a discoloration of the EVA on all the modules covering approximately 90% of the surface of the cell. The discoloration appears not only on the surface of the cell, but also on the road surface of the cell.

Fig.3: Discoloration of EVA

2. Peeling or delamination

Delamination occurs as a result of bond disintegration between the encapsulant and other layers of materials that form the PV module **[20]**.

It is manifested by a decrease in resistance leading to poor cell adhesion and even detachment of the layer.

Macben et al. **[21]** showed in their study that most of the delamination observed in the field takes place at the interface between the EVA and the solar cell because the interfacial force may initially be more limited than there between the EVA /glass. In this same study they found that delamination is more frequent and more severe in hot and humid countries. It promotes the penetration of moisture into the module and therefore causes various chemical reactions inside the module inducing damage such as corrosion of the metals of the module structure. In EVA encapsulation, the adhesion promoter is generally less stable than the additive, which limits the lifetime of the EVA even more than the peroxide used for crosslinking.

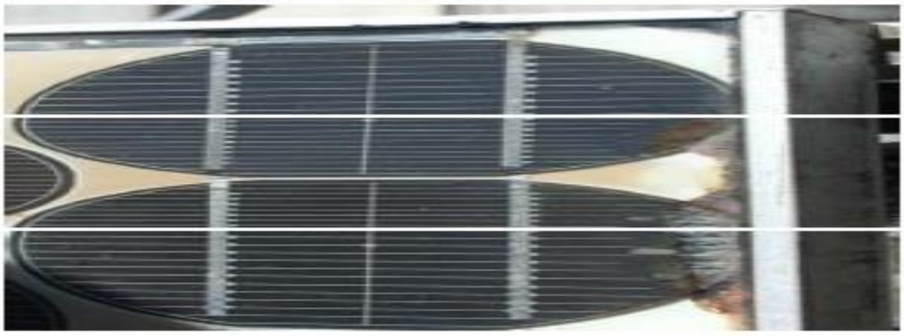

Fig. 4: Delamination

3. Junction boxes

The junction box is the container attached to the rear face of the module in order to protect the connection of the cellular chains of the external modules to the terminals. Typically, the junction box contains bypass diodes to protect the cells in a string in the event of a hot spot or shading. The failure observed in the field is most often the penetration of moisture which causes corrosion of the connections and chain interconnections in the junction area.

Fig. 5: Discoloration of the junction box

4. **Hot-spot phenomenon**

This phenomenon occurs when there is a low level of current occurring in a string of several high short circuit cells. If the series chain is short-circuited, the forward bias on all of these cells stresses the shaded cell. Hot spot heating occurs when a large number of cells connected in series cause a large reverse bias across the shaded cell, leading to large power dissipation in the bad cell.

Fig. 6 : Hot spot

5. **Cell cracking**

Glass breakage is an important factor in the degradation of PV modules. It occurs in most cases by aggression of a stone, during installation, maintenance and in particular during transport of the modules to their installation sites **[22]**. Modules that are broken or with cracks can continue to work properly. However, the risk of electric shock or moisture infiltration increases. Breaks and cracks are followed by other types of degradation such as corrosion, delamination, and discoloration **[20]**.

Once cell cracks are present in a solar module, there is an increased risk that during operation short cell solar module cracks may develop into deeper and wider cracks. This is due to mechanical stress caused by wind and weather conditions. A high number of broken cells per module shows a higher power loss.

Fig.7: Cell cracking

6. **Potential Induced Degradation**

The term Potential Induced Degradation (PID) was introduced into the English language in a study published by Pinguel et al. **[23]**. It was presented as a degradation mode resulting from voltage potential between cells in the PV module and ground. Research in this area has been pioneered by Jet Propulsion Laboratory, focusing primarily on electrochemical degradation in crystalline silicon in photovoltaic modules.
[24], **[25]**.

PID occurs when the potential voltage and leakage current of the module conduct ion mobility between the semiconductor material and the other elements of the module (for example between the glass and the lead frame), as shown in the following figure, thus causing the power output capability to degrade **[26]**.

In 2005, Swanson et al summarized data on inexplicable power losses at the large system level in a European Photovoltaics solar Energy conference. In their study, the cause of these losses was identified as PID, highlighting the issue and raising it for those in the solar industry **[27]**, **[28]**. Ion mobility increases humidity, temperature and potential voltage. The process is attributed to the influence of voltage, heat and humidity **[29]** .

7. Light Induced Degradation

Light Induced Degradation (LID) is a very rapid degradation mechanism that causes a loss of efficiency of 1 to 4% of p-type silicon in a few hours of exposure. The term LID for Light Induced Degradation was discovered by Staebler and Wronski in 1977 **[30]**. This mechanism has been the subject of numerous articles in journals and specialized publications. Behcara Nehme et al. **[31]** reviewed the different modes of degradation. In their studies, they showed that LID increases the recombination current in the base, and was just common in amorphous cells. LID was later observed in c-Si modules **[32]**, **[33]**, **[34]**. It is much more complex in CdTe and CIS/CIGS thin film modules and is still a subject of research. The LID produced on these modules unstable power variations which can be upwards or downwards, as reported in the various studies on the subject (degradation mechanisms), and which makes their performance measurement difficult. LID is known to reduce the lifetime of minority carriers in single crystal silicon substrates. The electrical and structural characteristics of the LID are currently not fully known. LID in solar cells has been studied by a relatively small number of research groups, from small sample sets **[35]**. Therefore, there is a large discrepancy in the results reported in the literature, and the details on the mechanisms of cell degradation are vague. Damiani **[36]** in his work reported that LID is associated with the formation of the well-known boron oxygen complex, which acts as a detrimental defect and consequently reduces the diffusion length of minority carriers.

5. CONCLUSION

In this article, we have listed the different most common degradation mechanisms in photovoltaic systems.

The use of these tools makes it possible to determine the reliability law of a system, depending on the conditions of use, in order to be able to predict its lifespan. However, the conduct of these studies can only be done if one has knowledge of the environmental specifications of the system and its failure modes. The best way to obtain this data is to follow a system in real operation in order to benefit from experience feedback. Another way is to conduct accelerated aging tests in order to produce a failure in a controlled and reproducible way, and to be able to prevent it by modifying the design of the system.

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