In situ monitoring of electrical parameters of PV modules under mechanical stress

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Introduction

The need of monitoring the quality of PV modules comes from the will of assessing their degradation in real outdoor conditions thanks to accelerated ageing [1]. Mechanical stresses are one of the PV modules stressors. In order to monitor the implied modes of degradation of PV modules, electroluminescence and flash testing are generally used [2][3][4]. However, these measurements are-time consuming because an accurate follow-up needs numerous handling of modules. Degradations could be evaluated more efficiently and accurately than with the usual IV and EL thanks to in situ DIV monitoring [5] and lock-in thermography imaging the failures detected by the in situ monitoring. On the one hand, in situ electrical monitoring would make it possible to avoid overly regular measurements, by signalling a change in the module's electrical characteristics. On the other hand, the use of alternative methods to electroluminescence, such as lock-in thermography (LIT), would make it possible to quantify and locate these electrical failures more precisely.

Topics and investigations

This study proposes a new method for the electrical tracking of photovoltaic modules. Here, this monitoring is applied to modules subjected to various mechanical loads:

- 3-point bending tests on one-cell and 4-cell modules;
- Manufacturing process of 4-cell plane and curved PV modules using different processes: lamination, Resin Transfer Molding and thermocompression.

The method developed involves dark I-V monitoring of the modules under load, and LIT measurements after loading. The dark I-V curves analysed provide access to the global electrical parameters of the cells, which enable to identify possible failures. In the case of bending tests, this makes it possible, among other things, to monitor the occurrence of a cell damage more closely, and to identify whether this damage can be foreseen or not. In the case of process monitoring, dark I-V characterisation is used to determine whether a process step breaks the cells, and if so, which step.
When a failure occurs, additional studies are carried out using LIT. This method of imaging gives a spatial location of the failures, and quantifies the local electrical parameters of the damaged modules. These maps, combined with finite element modelling of the module under these loads, provide a better understanding of the failure mechanisms.

Conclusions and perspectives

The proposed method offers an alternative to the methods already developed for monitoring the electrical health of modules under load. It allows a less time-consuming detection of the appearance of a failure thanks to in situ monitoring by dark I-V, and a more refined analysis of failures thanks to LIT measurements.
This method can be applied in particular for the monitoring of large modules under environmental conditions, or for the development of manufacturing processes [6]. Future studies will look at the sensitivity of this measurement to the number of cells in the module.

Explanatory pages

Aims

The aims of this study are to:

- Identify whether dark I-V electrical monitoring is a reliable method to detect the appearance of mechanical degradations in PV modules. Can it detect the appearance of small defects? How sensitive is it to the number of cells in the module?
- Understand the occurrence of cell breakage in photovoltaic modules when the module is stressed under bending load or during the different phases of its manufacturing process. Is the failure progressive or not? Where does it occur?
- Quantify the influence of the manufacturing process on the risk of failure of cells. Among lamination, Resin Transfer Molding and thermocompression, does any process imply more module failures under bending tests?

Methods

This study proposes a new protocol to monitor the electrical behaviour of a PV module. Usually, this monitoring is led with a combination of electroluminescence / flash tests (STC; AM1.5; $25^{o}C$) at regular time intervals during the ageing tests [1][4].
The protocol developed here consists in three phases:

1. Dark I-V monitoring of the module either under bending test, or during its process by different manufacturing processes of the module - Resin Transfer Molding (RTM) or thermocompression.
2. Analysis of the dark I-V measurements, extraction of the global electrical parameters of the module, and identification of a possible failure;
3. If a failure has been detected, further analysis of failures by lock-in thermography imaging, including identification of local electrical parameters.

a) Dark I-V monitoring of load cases

Two types of load cases are being studied.
On the one hand, bending tests are performed on modules of equivalent stacks, processed by different manufacturing processes: lamination, RTM or thermocompression. These one-cell modules are flat. A 3-point bending bench is used. The supports have two configurations: parallel to the bus bars or perpendicular to the bus bars. The module is placed in a bag in order to respect a complete dark. The mechanical loading is carried out on the front side of the module. A succession of loads is carried out. Dark I-V measurements are taken at each loading level and when returning to zero loading. These loading stages are gradually increased until an electrical modification of the cell is detected.
On the other hand, a dark I-V monitoring is applied during the manufacturing process of a PV module, either by RTM or thermocompression process. Measurements are regularly taken throughout the process. The breakage of a cell during the module manufacturing is detected by a change in the dark I-V curve.

b) Extraction of global electrical parameters

The dark I-V measurements are analysed during the loading process by a routine that allows the extraction of the global electrical parameters of the module [7]. The model used is the 1-diode model, which gives a more physical meaning to the extracted parameters than the 2-diode model. The evolution of the electrical parameters is observed as the module is loaded. As soon as a variation appears, the module is analysed by additional measurements using flash test (STC; AM1.5; $25^{o}C$) and lock-in thermography.

c) Fine measurement of local electrical parameters with lock-in thermography

Following the detection of a variation in the electrical parameters, additional measurements are carried out, by flash test (STC; AM1.5; $25^{o}C$) to observe the influence of this modification on the electrical performance, and by LIT to understand more precisely the origin of these electrical modifications (fig. 2). The tool Local I-V 2 is used to extract the local electrical parameters [8]. These results are compared with the global electrical parameters obtained from the dark I-V measurements.

The data accumulated in the course of the tests is compared with each other and allows the identification of the areas of fragility of the module, where failures appear first. These mappings are compared with a finite element mechanical simulation of the manufactured module, and correlated to the areas of stress concentration identified by this model.

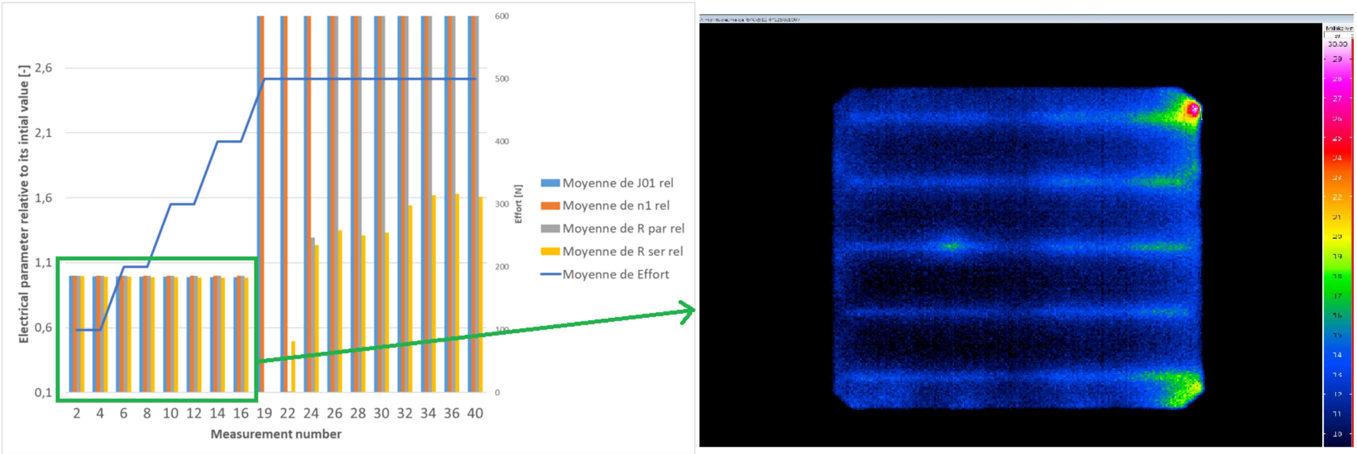

Figure 1: Left: Evolution of the electrical parameters extracted from dark I-V measurements during loading. On the left of the histogram (measurements 2 to 16), electrical parameters are very stable. Right: LIT measurement with forward bias (1V, 5A) associated to this state before the first failure.

Results

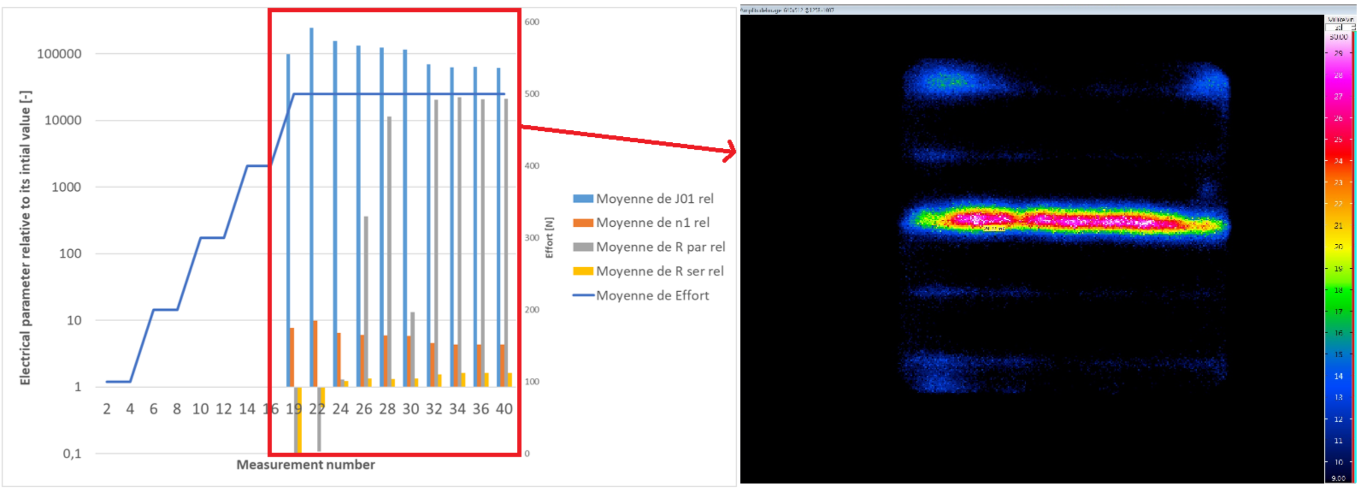

Figure 2: Left: Evolution of electrical parameters after the first failure (measurements 19 to 40). Electrical parameters stabilize after the 30th measurement. Right: LIT measurement with forward bias (1V, 5A) highlighting the appearance of series resistances associated with the breakage of the cell, following a 3-point bending load.

Bending tests performed on one-cell modules enabled to identify a general trend of variation of the electrical parameters over the course of loading. First of all, a zone of stability of the overall electrical parameters can be distinguished until a certain level of load, before any failure occurs (fig. 1). As soon as a failure occurs, the electrical parameters, in particular J_{01}, n_1 and R_{sh} diverge and then stabilise, after a few loading cycles, at a new value, meaning a stabilisation of the failure (fig. 2). Local electrical parameters of the PV module were confronted with the global parameters extracted from dark I-V measurements. Tests will be carried out to refine the understanding of the occurrence of the first breakage. Does it statistically always occur at the same load level and is the breakage progressive or sudden? Similar tests will be carried out on modules with 4 cells in order to identify the sensitivity of this method to the number of cells.
A comparative study of the tendency to breakage depending on the type of manufacturing process

used is in progress. Until now, only modules manufactured by lamination have been tested. Further tests will enable to identify whether alternative processes induce more failures or not.
Dark I-V monitoring of a manufacturing process enabled to identify electrical modifications when the module breaks at a certain step of the process.

References

[1] Rahul Khatri, Shivani Agarwal, Ivan Saha, Sunit Kumar Singh, and Bikash Kumar. Study on long term reliability of photo-voltaic modules and analysis of power degradation using accelerated aging tests and electroluminescence technique. 8:396–401. 1, 2

[2] Eric J. Schneller, R. Paul Brooker, Narendra S. Shiradkar, Marianne P. Rodgers, Neelkanth G. Dhere, Kristopher O. Davis, Hubert P. Seigneur, Nahid Mohajeri, John Wohlgemuth, Giuseppe Scardera, Andrew C. Rudack, and Winston V. Schoenfeld. Manufacturing metrology for c-si module reliability and durability part III: Module manufacturing. 59:992–1016. 1

[3] S. Kajari-Schröder, I. Kunze, and M. Köntges. Criticality of cracks in PV modules. 27:658–663. 1

[4] M. Sander, B. Henke, S. Schweizer, M. Ebert, and J. Bagdahn. Characterization of PV modules by combination of mechanical and electrical analysis methods. 1, 2

[5] Romain Cariou, Romain Couderc, Yannick Roujol, Adrien Bidaud, and Fabien Chabuel. Light and dark IV measurements correlations for space solar array failure detection in stowed configuration. In *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, pages 1665–1667. IEEE. 1

[6] Tatiana Duigou, Vincent Boichon, Xavier Brancaz, Fabien Chabuel, Pascal Francescato, Julien Gaume, Georges Habchi, Manuel Lagache, Philippe Saffré, and Lionel Tenchine. VIPV: Process development of integrated photovoltaic cells in a double-curved composite structure for automotive application. pages 1787 – 1790. 1

[7] Stephan Suckow, Tobias M. Pletzer, and Heinrich Kurz. Fast and reliable calculation of the two-diode model without simplifications: Fast and reliable calculation of the two-diode model without simplifications. 22(4):494–501. 2

[8] O Breitenstein and S Sturm. Lock-in thermography for analyzing solar cells and failure analysis in other electronic components. page 8. 2