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Experimental assessment of degradation rate in photovoltaic modules

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Abstract – **A test procedure is described in this paper that is conceived to investigate the degradation mechanism of PV modules based on different technologies. Environmental and mechanical stress factors are applied to the modules under investigation and electrical and electroluminescence characterization procedures are implemented to assess the module performance. Preliminary results are reported that refer to the application of the proposed test procedures to two sets of p-Si modules.**

Keywords – **Photovoltaic systems, degradation rate, electric variables measurement, uncertainty, data acquisition**

I. INTRODUCTION

Despite of the world-wide growing use of PhotoVoltaic (PV) plants for electrical energy production [1], parameters that allow the degradation rate of PV modules to be estimated on long time periods are rarely available. For thin-film based PV technologies, this kind of information is not provided, while for Si-based technologies the manufacturers often state a warranty in terms of maximum power warranted during the first 10 years and 25 years of operation, that is 90% and 80% of the initial maximum power, respectively. Unfortunately, information related to the phenomena responsible for this degradation and their time behaviour are not known, thus not allowing a reliable estimation of the pay-back time of a PV plant to be obtained. In the scientific literature, experimental results are described for outdoor exposed PV plants [2-5], but they only refer to Si-based modules and are based on the comparison between initial and final measurements after many years of operation in a non-controlled environment, thus not allowing the degradation rate to be estimated. An attempt in estimating such a trend has been made through the arrangement of the outdoor experimental PV laboratory described in [6-7], that has been conceived to monitor ten plants based on different PV technologies. The obtained results over a three-year period, which refer to both Si-based and thin-film based PV modules, are described on a monthly basis in [8]. These results can be summarized as follow:

- silicon technologies show lower degradation than thin-film technologies;
- string ribbon Si modules are more subjected to degradation than m-Si and p-Si modules;
- PV modules mounted on 2-axis tracking systems show higher degradation than the same PV modules mounted in fixed position.

The last result is in agreement with the conclusions in [9-11], where higher thermal and mechanical stresses are indicated as responsible for a fast degradation rate.

In order to better understand the degradation mechanisms of outdoor exposed PV modules, a series of laboratory tests and characterization procedures are here proposed. The tests are intended for reproducing outdoor conditions and also obtaining a convenient acceleration factor, thus minimizing the test time. The characterization procedures are based on the estimation of the electrical parameters of the tested PV modules and the application of the electroluminescence (EL) technique, which allows micro-cracking and other defects that result in power losses to be identified. With respect to the test procedures described in [12], which are mainly conceived to simulate a long-term degradation of PV modules, this paper focuses on tests designed to identify the PV degradation rate related to specific stresses.

II. TEST PROCEDURE

The proposed test procedure is based on the application of different stress factors to a set of PV modules of the same technology. Initially, the samples of each set (at least five units) are characterized in order to obtain their *I-V* characteristics and EL images. Then, the sample 1 is preserved by any stress in order to act as the reference module, while the other modules are subjected to environmental and mechanical stresses. At the end of each test cycle, all the modules of each set will be again characterized and the performance degradation will be estimated and correlated to each stress factor.

A. Stress tests

Environmental stresses are applied to two of the PV modules under test. The sample 2 is exposed to a damp-heat test, that is conceived to accelerate the water absorption in the PV module and then decrease its electrical insulation. The test is performed inside a climatic chamber that is set to perform a 24-hour cycle with relative humidity always higher than 90 %RH and temperature in the range of 25 °C to 55 °C. The sample 4 is instead subjected to thermal cycles in the range of -20 °C to 70 °C with a temperature rate of about 1 °C/min (6 cycles during a 24-hour test).

The other two samples of the set under test are subjected to mechanical stresses: cycles of static loads for the sample 5 and dynamic loads for the sample 3. An electrodynamic shaker is used for dynamic tests: the sample is mounted on the vibrating table of the shaker, which is driven in order to perform 5-hour random vibration cycles in the frequency range of 5 Hz to 150 Hz and a root mean square acceleration of 5 m/s^2.

B. Electrical characterization

The *I-V* characteristic curve of the PV modules under test has been initially measured by means of the capacitive-load technique, which requires to simultaneously acquire voltage, current, irradiance and temperature [13-14]. Current and voltage measurements have to be carried out at constant irradiance and temperature and the capacitance charging transient has not to exceed 100 ms [15]. Furthermore, in order to minimize the effect of parasitic parameters [16], it is suggested to use capacitance values that correspond to a total test time greater than 20 ms. Starting from these specifications, capacitances in the range of 0.5 mF to 1 mF have been used during the *I-V* measurements in outdoor conditions.

The measured *I-V* characteristics have been then corrected in order to refer them to the Standard Test Conditions (STC: standard spectrum 1000 W/m^2 and cell temperature 25 °C), using the correction procedure #1 suggested in the document [17]. The maximum power $P_{M,STC}$ at STC has been eventually obtained, which is the parameter used to assess the degradation of the PV modules under test.

Since not very large changes are expected for this parameter after each series of stress tests, the repeatability analysis of the characterization system and the uncertainty estimation of the measured parameter $P_{M,STC}$ are mandatory in order to obtain meaningful results. For the measurement uncertainty of the parameter $P_{M,STC}$, it has been estimated according to the model proposed in [8]. The expanded uncertainty (coverage factor $k = 2$) of the input quantities measured with the capacitive-load based system are:

- for the irradiance *G*, absolute uncertainty of 20 W/m^2 in the range (500 ÷ 1100) W/m^2;
- for the cell temperature, absolute uncertainty of 2 ° C;
- for the voltage *V* and the current *I*, relative uncertainty of 0.1% and 1% respectively.

The analysis has brought to measurement uncertainties that are similar to the estimated degradation after the first stress tests (see section III), thus making the obtained results questionable. In addition, the system repeatability is not low enough for the purpose of this work, mainly because the capacitive-load based system is tailored for PV modules that exhibit larger power. For these reasons, a new system has been arranged for the electrical characterization of the modules under test, which is based on a programmable electronic load connected to the PV module. The voltage across the module and the current the module provides are measured by means of two 6 ½ digit multimeters, while the irradiance *G* is sensed through a secondary standard pyranometer, whose voltage output is measured by means of another 6 ½ digit multimeter. All the multimeters and the programmable load are connected through a standard IEEE-488 interface to a Personal Computer, where a program runs that drives the load and acquires voltage, current and irradiance measurements. The air temperature is sensed through a Pt-100 Resistive Thermal Detector (RTD) and the cell temperature is estimated using the parameter NOCT of the module under test. The measured *I-V* characteristics are corrected to the STC using the same procedure [17].

For the new system, the expanded uncertainty ($k = 2$) of the input quantities are summarized below:

- irradiance *G*, 1.3% of reading and maximum offset of 7 W/m^2;
- voltage *V*, 20 ppm of reading and maximum offset of 10 μV;
- current *I*, 0.1% of reading and maximum offset of 40 μA;
- cell temperature, 2 °C.

In order to estimate the measurement uncertainty of the parameter $P_{M,STC}$, a numerical approach based on the Monte Carlo method [18] has been implemented by means of a MatLab script, in order to estimate a confidence interval of the measured parameter. An example of occurrence distribution of $P_{M,STC}$, that refers to a 5 W p-Si module and that has been obtained using 5000 trials is shown in the Fig. 1. In this case, the mean value is equal to 5.40 W and the 95% confidence interval is (5.32 ÷ 5.47) W.

The repeatability of the new characterization system has been estimated through repeated acquisition of *I-V* curves in similar conditions. Fig. 2 shows five *P-V* characteristics of two different p-Si modules with nameplate power at STC equal to 5 W and 10 W. The *P-V* curves at STC have been obtained implementing the procedure previously described to five *I-V* curves acquired in outdoor conditions at an irradiance of about
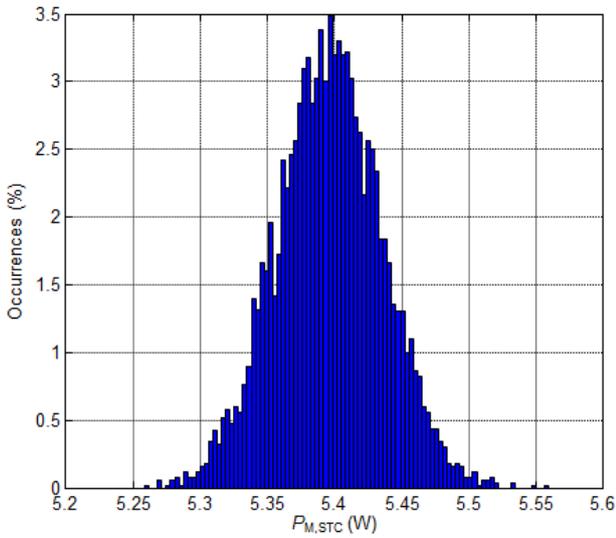
Fig. 1. Example of occurrence distribution of the measured parameter $P_{M,STC}$ obtained using the Monte Carlo method. The result refers to a 5 W p-Si module.

950 W/m² and with air temperature of about 30 °C. For the 5 W module, which is the same used to obtain the results of Fig. 1, the mean value of $P_{M,STC}$ is of 5.40 W and the standard deviation is of about 0.01 W, while for the 10 W module, mean and standard values of $P_{M,STC}$ are 10.65 W and 0.025 W, respectively. Similar results have been obtained for other modules with the same nameplate specifications, thus showing that the repeatability could be considered negligible with respect to other uncertainty contributions.

C. Optical characterization

With the aim of detecting the defects in the PV modules subjected to the stress tests, the electroluminescence (EL) technique is used. This technique is based on the application of a forward bias to a shaded PV module, which, in this condition, acts as a light emitting diode with an emission spectra in the range of about 950 nm to 1350 nm. A sensitive camera equipped with silicon charge-coupled device (CCD) or indium gallium arsenide (InGaAs) photodiodes is able to detect the emitted photons, thus obtaining an image where defective areas appear darker than perfect areas. In order to achieve a high signal-to-noise ratio and hence a clear image, the EL characterization of the PV modules has been performed inside a darkroom. The obtained images allow different defects to be highlighted, such as:

- micro cracks, which are mainly due to mechanical or thermal stresses and that usually evolve into broken cells;
- broken cells, which are characterized by electrically isolated areas that limit the current in the whole string;
- impurities and chain pattern, which are due to a low-quality production process and that appear like less shine areas in EL images;
- Potential Induced Degradation (PID), which is due to leakage currents with respect to earth, that in turn depend on high voltage and weather conditions.
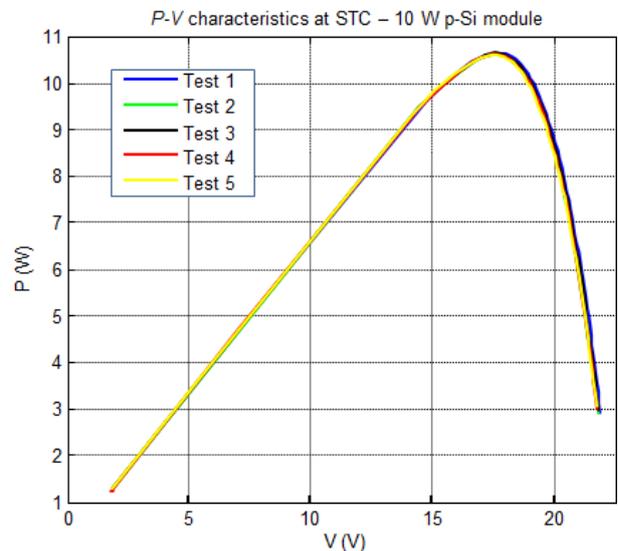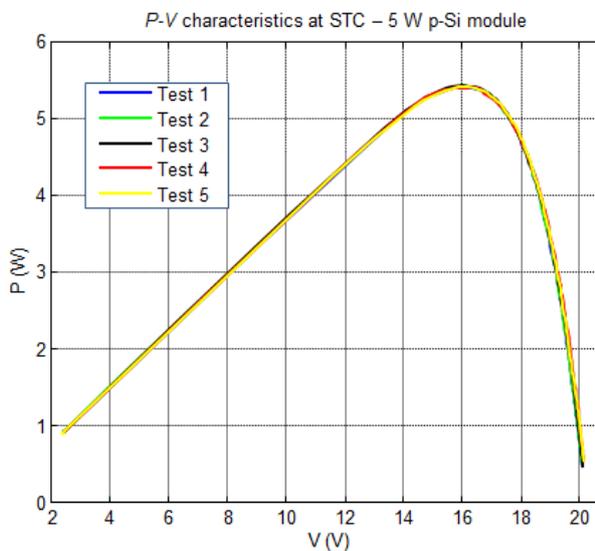

Fig. 2. Five P-V characteristics of two different p-Si modules with nameplate power at STC equal to 5 W and 10 W.

III. PRELIMINARY RESULTS

A. PV modules under test

The proposed test procedure has been implemented on two sets of p-Si modules: the first set includes five front-glass modules with a metallic frame, hereafter referred as m-modules, while the second set includes five semi-rigid plastic modules, hereafter referred as p-modules. The Table 1 reports the nameplate specifications of the tested PV modules.

The choice of low-size and low-power PV modules is related to the dimensions of climatic chamber and electrodynamic shaker that have been used to generate the stress quantities.

B. Initial characterization

Before applying environmental and mechanical stresses to the investigated PV modules, their *I-V* characteristics and their EL images have been obtained.

A summary of the results that refer to the initial $P_{M,STC}$ of each module obtained using the capacitive-load based system is reported in Fig. 3, where the red bars are the 95% confidence intervals of the parameter $P_{M,STC}$, while the blue lines are the nameplate maximum power at STC. One should note that m-modules (right-side of the figure) are consistent with their nameplate specification. On the contrary, three of the p-modules (p2, p3 and p5) show lower performance than the nameplate specifications (left-side of the figure). This result is in agreement with the obtained EL images: Fig. 4 shows the comparison between the modules p1 and p2, where the presence of important defects in the module p2 is highlighted.

C. Preliminary stress results

The two sets of investigated PV modules have been subjected to a first series of stress tests over a period of

Table 1. Nameplate specifications of the tested PV modules.

	m-modules	**p-modules**
Type	Front-glass with metallic frame	Semi-rigid plastic
Module size	40 x 28 cm	30 x 25 cm
Cells in series	36	34
Strings in parallel	1	2
$P_{M,STC}$	10 W	5 W
$V_{M,STC}$	17.5 V	16.0 V
$I_{M,STC}$	0.58 A	0.30 A
$V_{oc,STC}$	22.2 V	20.2 V
$I_{sc,STC}$	0.64 A	0.33 A

five months, as specified below:

- modules p2 and m2: ten cycles of damp-heat (DH) test - total test time: 240 h;
- modules p3 and m3: ten random-vibration (RV) sessions - total test time: 50 h;
- modules p4 and m4: sixty thermal cycles (TC) - total test time: 240 h.

The test plan and an example of the obtained results are shown in the Fig. 5, where the vertical bars I-V/EL tag the instants the characterization of the PV modules has been performed. The results in the bottom part of the figure show a significant degradation of module p2 due to the damp-heat stress and of module p4 due to the thermal stress, with a relative change of the parameter $P_{M,STC}$ of – 4.9% and – 6.2%, respectively.
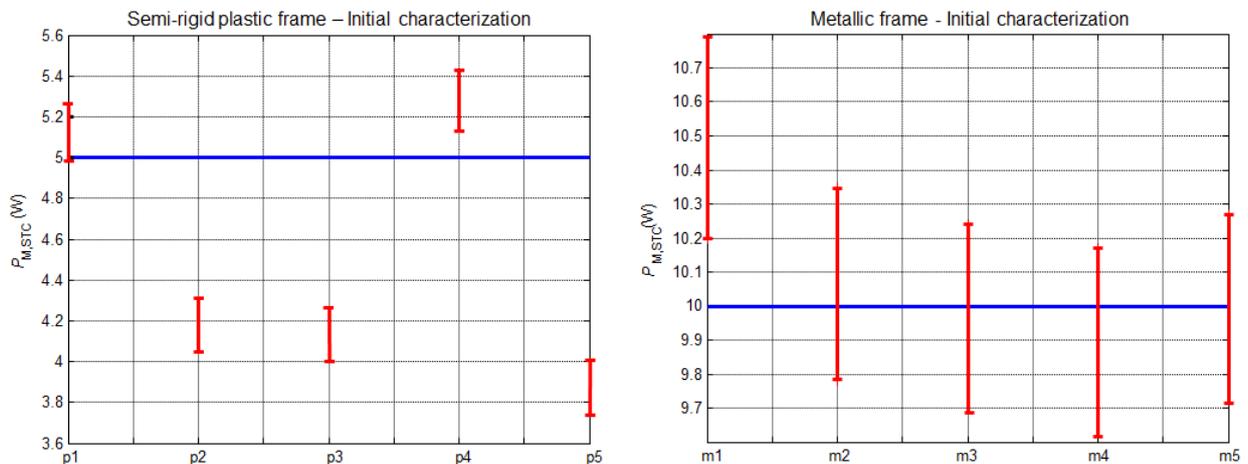

Fig. 3. Result summary of the initial I-V characterization obtained with the capacitive-load based system: the red bars are the 95% confidence intervals of the parameter $P_{M,STC}$, while the blue lines are the nameplate maximum power at STC.
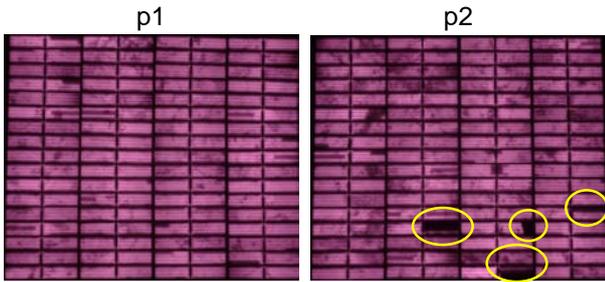
Fig. 4. Initial EL images of modules p1 and p2: the yellow circles in the p2 image highlight the main defects.

However, the large uncertainty of the parameter $P_{M,STC}$ provided by the capacitive-load based system makes these results questionable and does not allow a degradation to be observed on the other modules subjected to stress tests.

A comparison of EL images of module p4 before and after the thermal cycle stress test is shown in Fig. 6, where the main defects related to the stress test are highlighted.

IV. CONCLUSIONS

The preliminary results obtained after a first series of stress tests have shown the effectiveness of the proposed procedure. Between the two sets of tested p-Si modules, the one encapsulated in a semi-rigid plastic frame have shown a greater sensitivity to environmental stresses than the one with a metallic frame. However, for both sets the large uncertainty of the estimated parameter $P_{M,STC}$ has not allowed other possible degradation of the module performance to be highlighted. For this reason, the authors have arranged a new system for the electrical characterization of the modules under test, obtaining a reduction of the measurement uncertainty. Future tests will be performed using the programmable-load based system for the electrical characterization of the PV modules under test. Also thin-film based modules will be included in the test set, in order to confirm the results obtained in the outdoor PV experimental laboratory.

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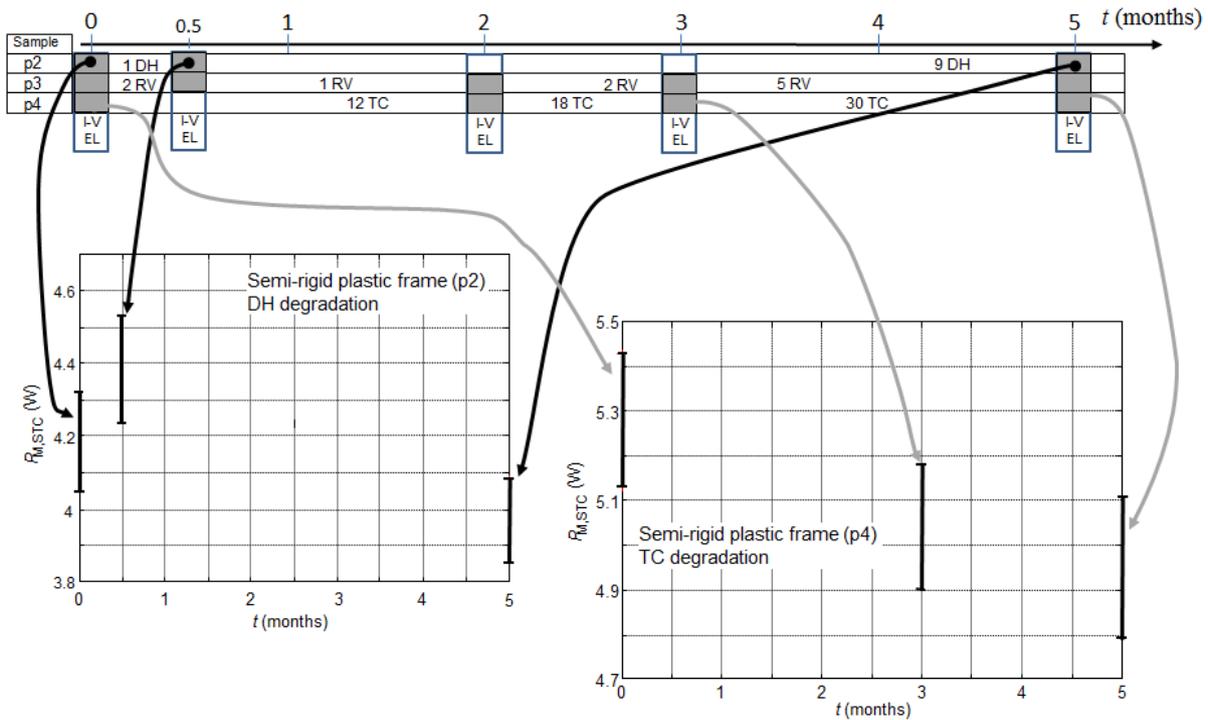
Fig. 5. Summary of the tests carried out on the investigated PV modules over a five-month period (top part of the figure) and example of the obtained results on the modules p2 and p4 (bottom part of the figure) using the capacitive-load based system.
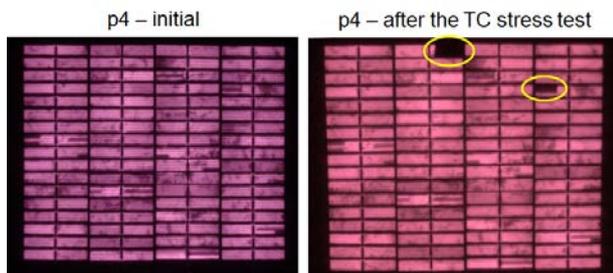
Fig. 6. EL images of module p4 before (left side) and after sixty thermal cycles (right side): the yellow circles in the right-side image highlight the defects related to the stress test.

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