Preliminary studies on the distribution of lightning current in the components of PV modules

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***Abstract*—This paper presents tests in photovoltaic module assembly whose objective is to verify the behavior of the connections of its components when conducting portion of the lightning current. The tests conducted on the arrangements showed that for the direct current pulses, simulating continuing currents, they did not damage the connections or the modules used.**

***Keywords*—components of connections, LPS for PV systems.**

I. Introduction

Photovoltaic systems generate electricity from exposure to the sunlight, and because this they are exposed to lightning, the main source of damage in these systems.

When reaching the photovoltaic systems, lightning can cause perforations in the photovoltaic modules, in the module frames [01-02], burning inverters and string boxes, among other types of damages.

The protection against direct impact of lightning in the modules set, whether they are mounted on the ground or in rooftops, can be done through an isolated Lightning Protection System –LPS (see Figure 1) or by small rods (air-termination system) installed in the fixing structure of the modules or in their frames (as shown in Figure 2).

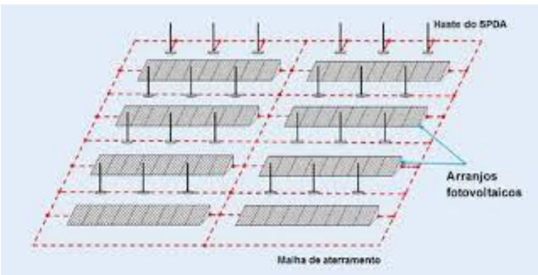

Fig. 1: Isolated system (Figure from [3])

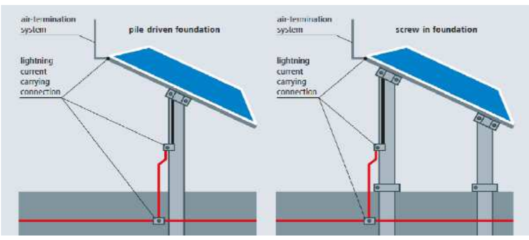

Fig. 2: Air-termination system (small rods) installed in the frames of the module (Figures from [4])

The small rods are positioned according to the rolling sphere or protection angle methods. The modules must be entirely within the protection volume provided by the air-termination system (see Figure 3).

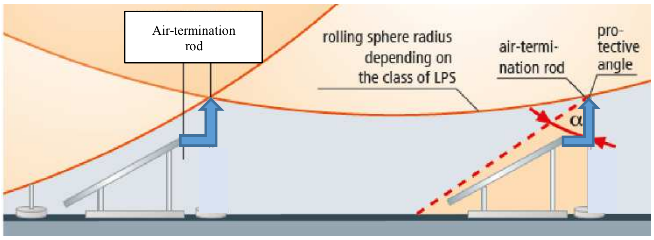

Fig. 3: Rolling Sphere Method and Protective Angle Method (Figure adapted from [4])

The air-termination system must not shade the PV modules, this may cause a decrease in power generation. Thus, in general, isolated LPS results in the need for a larger area for the installation of a photovoltaic generation plant [5].

The installation of small "L" shaped rods fixed to the structure or to the modules' frames is a good option in relation to isolated systems, optimizing material, and the area needed for the system. However, in this option, when struck by lightning, the impulsive current passes through the rod, and will be distributed to the connector of the rod, and from it to the structure or to the frame, until it reaches the earth-termination system [6].

A part of the lightning current will pass through the photovoltaic system cables, the earth-termination system cables and surge protection devices that must be properly sized to protect the system, especially the inverters [7].

The main objective of this paper is to verify the behavior of some components of the air-termination, frames and down conductor systems when conducting lightning currents.

The continuing current is one of the lightning current components responsible for the most significant thermal effects. This lightning current component perforates metal sheets, melts metal parts at the point where the discharge reaches the structure or the LPS, perforates the photovoltaic modules, starts fires when reaching trees or combustible roofs.

The simulation of this component in the laboratory is done through pulses of direct current with the adjustment of the current value and the pulse's duration, thus regulating the pulse charge in coulombs (C).

This work presents preliminary experimental developments in arrangements formed by a module, its structure, and the ground connection, with the small rod installed in the frame, or in the structure and all the necessary connections. The sets are subjected to continuing currents generated in the laboratory whose results are added to those from the electrical resistance measurements of the samples. Comparisons were made between the tests to determine I/V characteristics, and insulation resistance performed on the module before and after the tests related to lightning currents.

Future work should be carried out in order to complete this paper, mainly with regard to tests with other components of lightning, for example, the first return stroke that, due to its high value and waveform, small sparks can occur in the connections. due to the current density at these points. In the laboratory used, the generation of impulsive currents, mainly with a waveform of the 10/350µs, which is the standardized one, is not possible; hence, these experiments should be carried out in another laboratory for future work.

II. EXPERIMENTAL DEVELOPMENTS

A. Samples

An arrangement (called Arrangement 01) is formed by a photovoltaic module, its structure, all its fixing components, connection with the earth-termination system, and a small rod installed at one end point of the structure. The arrangement 02 is formed by the photovoltaic module, its structure, all its fixing connectors, connection to the earth-termination system, and a small rod installed at one end of the module frame point.

In these two arrangements, the electrical resistance was measured, and direct current pulses were applied to simulate the continuing current component. The module was submitted to tests to determine I/V characteristics and insulation resistance before and after tests related to lightning currents.

The module used has the following nominal characteristics: ASE manufacturing; model ASE-050-ALF/17; serial number 18390; nominal ratings at 1000W/m² irradiance, temperature 25ºC, P_p: 50 W_{DC}; V_{oc}: 21.3 V_{DC}, Vp: 17.2 V_{DC}, I_{sc}: 3.2 A_{DC}, I_p: 2.9 A_{DC}; Design load 50 PFS; for field connections, use minimum #16 AWG sunlight resistant wire insulated for a minimum of 90ºC; Max. Fuse series: 5 A; Max. System voltage: 50 V_{DC} (see Figure 4).

The structure used in the tests is made of steel specially assembled, but with parts used in real assemblies (see Figure 5).

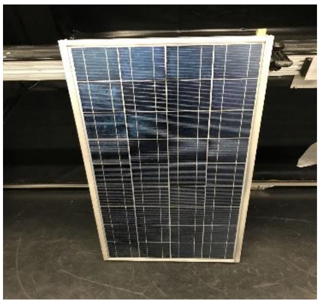
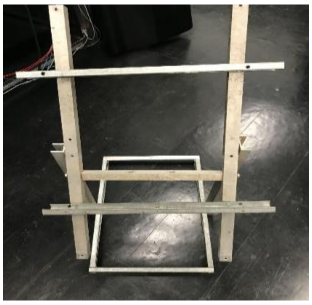

Fig. 4: Module used in the tests - Fig. 5: Structure used in the tests

Figure 6 shows some types of connectors used to fix the module, and Figure 7 shows the small rods used.

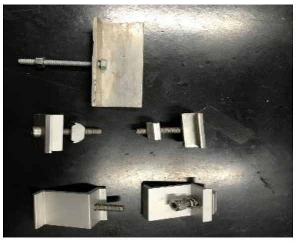
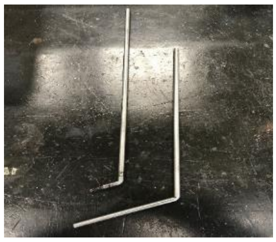

Fig. 6: Connectors used for fixing the modules - Fig. 7: Small rods used in the tests

B. Tests performed

Initially, the module was submitted to tests to determine I/V characteristics (SOLAR TEST 01), dry insulation resistance (DIT 01), wet insulation resistance (WIR 01) and Electroluminescence test (EL 01).

After assembling the arrangement with the module, structure, rod installed at the upper end of the structure and grounding, the electrical resistance was measured from the rod's tip to a marked part of the grounding conductor. A four-point micro ohmmeter with a full scale of 100 A was used to measure the electrical resistance (ER 01).

A second arrangement was assembled, and this time the rod was installed at one end of the module frame. Electrical resistance was measured.

Each of the arrays was subjected to pulses of direct current in the form of an arc at the rod's tip, simulating the continuing current (CC 01). The charge values of the continuing current used are those described in Table 3 of the Brazilian standard for lightning protection, ABNT NBR 5419-1 [8], which is based on IEC 62305-1 [9] and represent the maximum values of the lightning charge for protection levels III-IV, II and I.

These direct current pulses were carried out at the High Currents Laboratory of the Institute of Energy and Environment of University of São Paulo. A 3MVA three-phase transformer and a full-wave bridge rectifier were used as source. This pulse was applied in the form of an electric arc on the tip of the rods (see Figure 8).

Figure 8: Arc in gap during the test

The current was about 500 A, and the charge was adjusted through the duration of the pulse.

In Figure 9, electrode "1" is a SAE 1020 steel electrode connected to the source, the mini rod ("2") is also made of SAE 1020 steel, including the GAP of approximately 3 centimeters. Current pulses pass through "1"; then by the arc-shaped "GAP"; then by "2"; by the module frame; through the connectors; by the module assembly structure; by a pressure terminal; by copper insulated cable; returning to the source by 4 conductors in parallel ("3"). This return by these 4 conductors is done equidistantly from the location of the arc to confine it to the GAP.

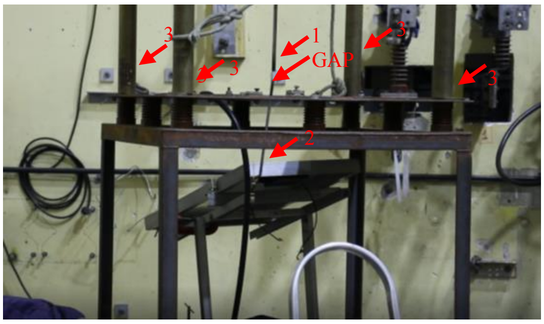

Figure 9: Test assembly

After each pulse of direct current, the respective electrical resistances were measured.

In each arrangement, three pulses of direct current were applied increasingly: 150 C, 225 C, and 300 C.

After these applications and electrical resistance measurements, each module was submitted to I/V characteristics (SOLAR TEST 02), dry insulation resistance (DIT 02), wet insulation resistance (WIR 02) and Electroluminescence test (EL 02) tests.

III. ANALYSIS OF TESTS AND MEASUREMENTS

The main objective of this preliminary study is to verify what happens to the connections when they are conducting the lightning continuing current component.

Damage analysis is conducted by visual inspection and by measuring the electrical resistance of the assembly. At the points of contact, there may be a fusion of material, leading to a decrease in electrical resistance. In this case, the system was dismantled to check the melting points.

Another purpose of this study is to verify some variation or degradation of the module regarding its electrical characteristics when subjected to direct current pulses. The electrical characteristics were evaluated through the tests in the module (SOLAR TESTS, DIT, WIR, EL).

Electroluminescence and wet insulation resistance tests were also performed on the modules before and after the continuing current tests.

A. Test results before application of continuing current

The tests on the module were carried out in the laboratories of the Technical Service of Photovoltaic Systems of the Energy and Environment Institute of São Paulo University.

To obtain the I/V characteristics (SOLAR TEST 01), a solar simulator, Pasan, Model High Light 3 LTM, Accuracy Class A+A+A+, was used, which aims to determine the electrical characteristics of the module under standard conditions of test: STC – Standard Test Conditions (25ºC; AM 1.5 and 1000W/m²).

This determination was made in accordance with the procedures described in item 10.2 of the IEC 61215 standard [10]. Figures 10 and 11 show the results of the test (SOLAR TEST) before the continuing current simulation applications.

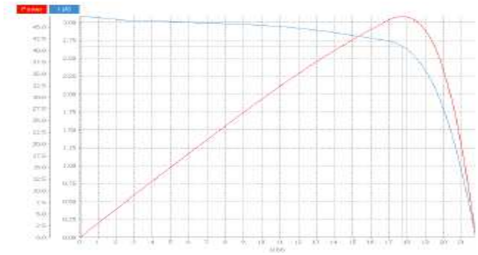

Fig. 10: Maximum power determination and I/V curves before current tests

Direct			Irradiance Channel 4
Monitor cell temperature	25.43 °C	Fill factor	70.57 %
DUT temperature	25.51 °C	Cell efficiency	13.38 %
Compensated	25.00 °C	DUT efficiency	10.83 %
Gavg	1000.57 W/m²		
GstdDev	0.08 W/m²		
Compensated Irradiance	1000.00 W/m²		
Regression linear for Voc	21.766 V		
Linear regression Isc	3.074 A		
Regression linear for	0.828 Ω		
Regression linear for	80.773 Ω		
Maximum power	47.221 W		
Voltage at Maximum	17.756 V		
Current at Maximum	2.659 A		

Fig. 11: Characteristic data of the module obtained in the tests to determine the maximum power before the tests

The dry electrical insulation test (DIT 01) verified the electrical insulation between the electrical terminals (positive and negative) of the module and its metallic frame and was carried out as specified in item 10.3 of the IEC 61215 standard [10].

It was used in this test a monometer, brand Fluke, Model 1550B, accuracy class 5%. Table I shows the results obtained. In this test, the laboratory temperature was 26.3ºC and the humidity was 76%.

Table I: Insulation resistance before the electrical current test (DIT 01)

ITEM	Designation				Accordance
10.3	Insulation Resistance				in accordance
10.3.5	There must be no dielectric rupture or surface tracking according to IEC 61215 - Clause 10.3.4 - item C				
	Maximum System Voltage:	50 V			
	For modules with an area greater than 0.1 m², the product between the measured insulation resistance must not be less than 400 MΩ				in accordance
	1135 V / 1 minute		266 V / 2 minutes		
	Resistance	3.93 GΩ	Resistance	11.50 GΩ	
	Area (m²)	0.436	Area(m²)	0.436	
	Value (GΩm²)	1.71	Value (GΩm²)	5.02	

The Insulation Resistance test in humidity conditions (WIR 01) checks the electrical insulation between the electrical terminals (positive and negative) of the module and its metallic frame in humidity conditions and was conducted as specified in item 10.15 of the IEC 61215 standard [10]. In this test, the same instrument described for the DIT 01 test was used. Table II shows the test results.

Table II: Insulation resistance in wet condition before the current test

ITEM	Designation		Accordance
10.15	Insulation resistance in wet condition before the current test (WIR 01)		in accordance
	Evaluate the module's insulation when it´s wet and verify that moisture from rain, dew, or melting snow does not enter in the energized parts of the module circuit, where it can cause corrosion, a ground fault, or a safety hazard.		
	Maximum System Voltage:	50 V	
	For modules with an area greater than 0.1 m², the product of the measured insulation resistance must be greater than 40 MΩ x m²		in accordance
	Applied Voltage	266 V / 2 minutes	
	Resistance Measured	18.0 GΩ	
	Area (m²)	0.436	
	Resistance x area (GΩm²)	7.85	

The Electroluminescence Test was carried out in accordance with IEC TS 60904-13 [11], item 4.1.1: Photovoltaic devices - Part 13: Electroluminescence of photovoltaic modules.

It was used a digital camera, Canon, Model EOS Rebel T6, 18 Mega pixels, with EF-S 18-55 mm f/3.5-5.6 III and EF-S 55-250mm f/4-5 IS II lenses; a voltage source, Magna Power Electronics; a digital thermohygrometer unity, model THU-200, with accuracy class: +/- 1ºC for temperature and +/- 5% humidity.

In this test the photovoltaic module is connected to a DC power supply, and the applied current is 100% of the short-circuit current of the photovoltaic module. The test is performed in the dark environment, in such a way as to capture the emitted spectrum, and the exposure time to this current being approximately 30 seconds.

Figure 12 shows the photo obtained in the test.

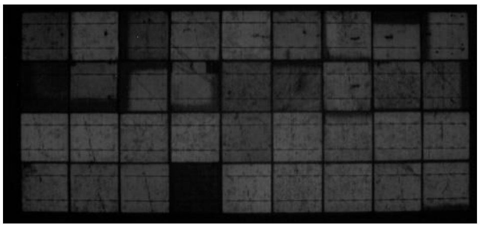

Figure 12: Electroluminescence test before current tests.

B. Tests simulating continuing currents

Before and after the tests simulating the continuing currents, the electrical resistances of the assemblies were measured from the tip of the mini rod to the grounding point of the arrangement. Table III shows the electrical resistance values of these sections of arrangement 1 and 2.

Table III - Measurement of electrical resistance before and after tests with current - Arrangements 1 and 2

	Before current tests (μΩ)	**After current pulse with 150C (μΩ)**	**After current pulse with 225C (μΩ)**	**After current pulse with 300C (μΩ)**
ARRANGEMENT 1	1154	1255	1264	1257
ARRANGEMENT 2	1197	1248	1276	1266

The values used in the tests to simulate the continuing current (direct current pulse) are described in Table IV.

Table IV: Test with direct current pulses

	APPLICATION (+/- 20%)	CURRENT (A)	TIME (ms)	CHARGE (C)
ARRANGEMENT 1	1 (150C)	527	320	168
ARRANGEMENT 1	2 (225C)	521	432	225
ARRANGEMENT 1	3 (300C)	532	620	330
ARRANGEMENT 2	4 (150C)	538	320	172
ARRANGEMENT 2	5 (225C)	522	437	235
ARRANGEMENT 2	6 (300C)	525	617	324

Figure 13 shows an example of an oscillogram (in this case, application 3 in arrangement 1) of the direct current pulse.

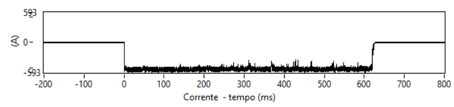

Fig. 13: Application Oscillogram 3

C. Results of tests on the module after tests with continuing current

The tests conducted on the modules after the direct current pulse tests that simulate the continuing currents were conducted under the same conditions as those conducted before. The same laboratory and the same instruments were used. The results of the I/V characteristics after the tests with current (SOLAR TESTS 02) are in Figures 14 and 15.

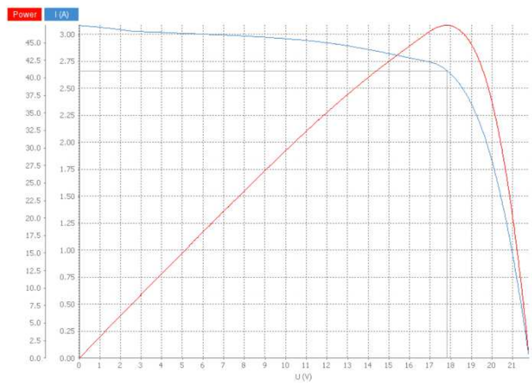

Fig. 14: Maximum power determination and I/V curves after current tests

Direct			Irradiance Channel 4
Monitor cell temperature	25.88 °C	Fill factor	70.75 %
DUT temperature	25.96 °C	Cell efficiency	13.44 %
Compensated	25.00 °C	DUT efficiency	10.87 %
Gavg	999.63 W/m²		
GstdDev	0.16 W/m²		
Compensated Irradiance	1000.00 W/m²		
Regression linear for Voc	21.799 V		
Linear regression Isc	3.074 A		
Regression linear for	0.812 Ω		
Regression linear for	80.907 Ω		
Maximum power	47.405 W		
Voltage at Maximum	17.821 V		
Current at Maximum	2.660 A		

Fig. 15: Characteristic data of the module obtained in the tests to determine the maximum power after the tests

Table V shows the results obtained in the insulation resistance tests after the current tests (DIT 02). In this test, the laboratory temperature was 25.6ºC and the humidity was 71%.

Table V: Insulation resistance after the current test (DIT 02)

ITEM	designation				Accordance
10.3	Insulation Resistance				in accordance
10.3.5	There must be no dielectric breakdown or surface tracking according to IEC 61215 - Clause 10.3.4 - item C				
	Maximum System Voltage:		50 V		
	For modules with an area greater than 0.1 m², the product between the measured insulation resistance must not be less than 400 MΩ				in accordance
	1135 V / 1 minute		266 V / 2 minutes		
	Resistance	8.3 GΩ	Resistance	24.50 GΩ	
	Area (m²)	0.436	Area (m²)	0.436	
	Value (GΩm²)	3.62	Value (GΩm²)	10.69	

Table VI shows the results of the insulation resistance test under humidity conditions (WIR 02) after the tests with current.

Table VI: Wet insulation resistance after the current test (WIR 02)

ITEM	designation		Accordance
10.15	Insulation Resistance in humid conditions		in accordance
	Evaluate the module's insulation when wet and verify that moisture from rain, dew, or melting snow does not enter the live parts of the module circuit, where it can cause corrosion, a ground fault, or a safety hazard.		
	Max. System Voltage:	50 V	
	For modules with an area greater than 0.1 m², the product between the measured insulation resistance must not be less than 40 MΩ x m²		in accordance
	Applied voltage	266 V / 2 minutes	
	resistance	23.5 GΩ	
	Area (m²)	0.436	
	resistance x area (GΩm²)	10.25	

Figure 16 shows the result of the electroluminescence test after current submission.

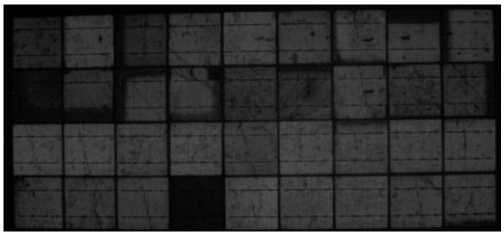

Figure 16: Electroluminescence test after current tests.

D. Analysis of results before and after tests with continuing current

The first check after the tests was the visual, mainly in the connections between the structure and the module. Different connectors were used and when dismantled it was found that all connections were intact, with no marks on the contacts, no welding or damage. The figures 17 a), b), c) and d) show the connectors after the electrical current tests.

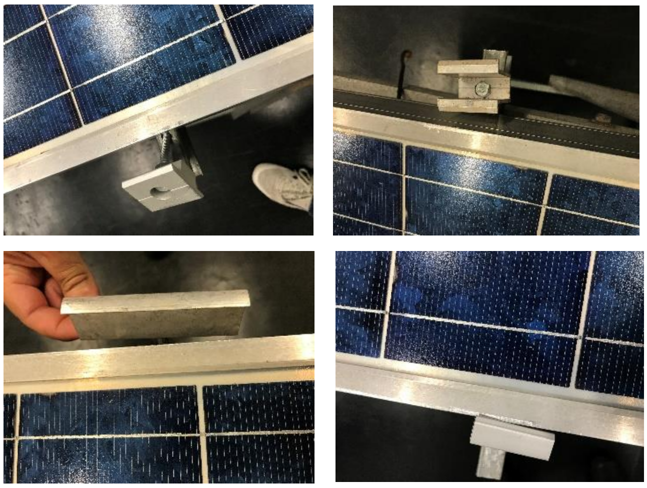

Figure 17 a), b), c) e d): Connectors after current tests.

Regarding the electrical resistance measurements in the two arrays, they behaved in the same way. In arrangement 1 there was an increase of 8.7% between the measurement performed before the tests with current and after the application with 150C; an increase of 0.7% between the measurement performed at 150C and after application at 225C and a decrease of 0.5% between the measurement performed at 225C and after application at 300C.

In arrangement 2 there was an increase of 4.2% between the measurement performed before the tests with current and after the application with 150C; an increase of 2.2% between the measurements performed at 150C and after application at 225C and a decrease of 0.8% between the measurement performed at 225C and after application at 300C.

The differences between measurements before the current pulses and those after each pulse are slightly larger (8.7% for array 1 and 4.2% for array 2). The reason may be due to a small movement in the positioning arrangements for the tests and to the measurement uncertainty itself. The other differences between the other measurements are within the measurement uncertainty, so it can be considered that there was no variation between the values.

We compared the values of "Maximum power", "Voltage at maximum power", "Current at maximum power" and "Cell efficiency" obtained in the I /V characteristics test before and after the tests with current pulses. The table VII shows the differences between the obtained values.

Table VII - Comparison between module characteristics

Characteristics	Module before current tests	Module after current tests	Difference
Max. Power	47.221 W	47.405 W	1.004 x
Voltage at max.	17.756 V	17.821 V	1.004 x
Current at max.	2.659 A	2.660 A	1.0004 x
Cell efficiency	13.38 %	13.44 %	1.004 x

We can verify that the values before and after the continuous current pulses remained the same, with the small variations being within the measurement uncertainties.

The tests of insulation resistance dry and wet before and after the tests with currents pulses are shown at Table VIII.

Table VIII - Comparison between tests of insulation

Test	**R at 1135V/1 min (Dry test)**		**R at 266V/2 min (Dry test)**		**R at 266V/2 min (Wet test)**	
Before	R=3.93 GΩ	1.71 GΩm²	R=11.5 GΩ	5.02 GΩm²	R=18.0 GΩ	7.85 GΩm²
After	R=8.3 GΩ	3.62 GΩm²	R=24.5 GΩ	10.69 GΩm²	R=23.5 GΩ	10.25 GΩm²

For modules with an area greater than 0.1 m² (in this case 0.436 m²), the product between the measured insulation resistance must not be less than 400 MΩ x m² (dry tests) and 40 MΩ x m² (wet tests). The tests results showed values higher than 1 GΩ x m².

Analyzing the electroluminescence tests before and after the tests with current, we verified that the module used was not new and had problems. Initially, the objective of the study was only the connector's verification in relation to the conduction of the continuing current. The following problems were found through the electroluminescence test on the module:

- Micro cracks in 6 cells
- Dark stripes in the finger's direction and on the busbar (defects in the metallic contacts) in 5 cells
- Significant black dots in 18 cells
- Partially erased areas (due to degradation) in 12 cells
- Dark cells (significantly darker compared to the rest of the cells) in 2 cells.

These problems did not worse after the current pulses, and it can be considered that there was no change in the module after the pulses.

In general, we can say that there was no change in the module or in the connections due to the continuing current components to which the arrangements were submitted.

Although it was not the purpose of this work, it was not possible, due to the characteristics of the available laboratories, to subject the arrangements to impulsive currents to simulate the return stroke currents and subsequent currents, which, due to the high current densities in the connections, could present small sparks in them and, eventually, some damage.

The greatest damage was, obviously, at the ends of the mini rods used, where the arcs occurred due to the applied current pulses. Figures 18 a) and b) show these tips after the tests.

Figure 18: Tips of mini rods after tests

IV. Conclusions

The easiest and lowest cost protection against direct lightning in photovoltaic arrays is the installation of small rods in the modules' frames or their fixing structures.

This study presents the behavior of some types of connectors when conducting the continuing currents of lightning.

The tests conducted on the arrangements showed that for the current pulses, simulating continuing currents, they did not damage the connections or the modules used.

These tests are part of a preliminary study, since laboratory simulations using impulsive currents (first return stroke and subsequent stroke) were not performed.

The use of small rods installed directly on the photovoltaic modules structures or frames is a good practice, since, if properly designed, they will not shade to the modules nor a substantial increase in the area necessary for the protection of these systems against direct lightning.

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