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Studying the effect of the impulse voltage application on sc-Si PV modules

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ABSTRACT

In the present work, the impact of standard impulse lightning voltage strikes (1.2/50 μs) on the performance of single-crystalline silicon photovoltaic modules (whose construction has been assessed by IEC 61730) is evaluated. Tests are carried out according to the IEC 61730-2 Standard, while one of the main claims of the present work refers to extreme tests with voltage levels far beyond those proposed by the above Standards. The performance is evaluated by means of I-V and P-V characteristic curve recording for the module under test, followed by a detailed comparison with the corresponding curves of a reference module. The data are reduced to Standard Tests Conditions according to IEC 60891:2009. Special attention is paid on the consideration of possible sources of inherent measuring errors, for reliable comparison between the reference and the stressed module. The results suggest that, neither power nor mechanical degradation is induced on the photovoltaic module for voltages up to the limits imposed by the IEC 61730-2 (i.e. 12 kV peak). Interestingly, the module withstands voltages up to 35 kV peak, as far as the rest procedure of the Standards is strictly followed. Finally, tests in “rod-to-module” gap are performed to simulate direct lightning strikes on the module, showing that a peak voltage as high as 144 kV is needed for destructing the module, both electrically, thermally, and mechanically.

1. Introduction

The widespread adoption of photovoltaic (PV) systems (both grid-connected and standalone) is dominant topic nowadays. The ongoing climatic change due to excessive use of polluting fossil fuels in order to meet the increasing electricity demands, and the exhaustion of conventional energy deposits, make PVs a promising solution. However, the extended use of PVs raises various issues. Among those issues, photovoltaic modules and relative electronics protection against internally (switching) and externally (lightning) induced over-voltages and current surges, is a vital one and has attracted increasing research interest (Christodoulou et al., 2015a,b; Takahashi et al., 1990; Hernandez et al., 2008; Hernandez et al., 2014; Carmichael and Noel, 1985; Stern and Karner, 1993; Häberlin and Minkner, 1994; Häberlin, 2001; Higo et al., 2014). Indeed, photovoltaic modules are more vulnerable to direct lightning strikes than conventional low-voltage power distribution systems, due to installations on roofs, facades of buildings, and in general on unsheltered areas. Earth electrodes (Christodoulou et al., 2015; Alagmir and Ahmed, 2015; Tu et al., 2013), ground wires (Tu et al., 2013; Charalambous et al., 2014a, 2014b; Kokkinos et al., 2012; Wang et al., 2011), surge arresters (Kokkinos et al., 2012; Wang et al., 2011; Pons and Tommasini, 2013; Lightning and Surge protection for rooftop photovoltaic systems (white paper), 2015; Lightning and Surge protection for free field power plants (white paper), 2015; Common Practices for Protection against the Effects of Lightning on Stand-Alone Photovoltaic Systems, 2003; Amicucci et al., 2012) etc have been employed as protection methods of PV systems, just to name a few. Lightning and surge protection is the main matter of the IEC 62305 Standard (Parts 1 to 4) Protection against lightning—Part 1, 2010; Protection against lightning—Part 2, 2010; Protection against lightning—Part 3, 2010; Protection against lightning—Part 4, 2010, while IEC 61643-12 Standard (Low-Voltage surge protective devices, 2008) describes the selection and application principles of surge protective devices (SPDs).

On the other hand, efficient protection designs should be based on data related to PV module behavior under real tests with overvoltages and current surges. Although, very interesting works on high voltage tests of PVs do exist (Dechthummarong et al., 2011; Jiang and Grzybowski, 2014; Jiang and Grzybowski, 2013; Jiang and Grzybowski, 2014; Sekioka, 2012; Naxakis et al., 2016b), liter-

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ature remains quite poor at the moment, especially if we are looking for lightning tests according to up-to-date International Standards. The present work intends to contribute towards this direction.

Thus, the present work is based on the IEC 61730-2:2004 Standard (IEC 61730-2, 2004) and as well on the revised version of it, i.e. IEC 61730-2:2016 (IEC 61730-2, 2016). These Standards describe the testing requirements for PV modules in order to provide safe electrical and mechanical operation during their expected lifetime. In the above documents, test sequence and pass criteria are designed to detect the potential breakdown of internal and external components of PV modules that would result in fire, electric shock, and personal injury. Specifically, this article deals with the Impulse voltage test MST 14 (MST stands for "Module Safety Tests"), applied on modules whose construction has been assessed by IEC 61730, in the city of Patras (Greece; 38°17′18.5″N 21°47′21.8″E). MST 14 is to verify the capability of insulation of the PV module to withstand over-voltages of atmospheric origin. It also covers over-voltages due to switching of low-voltage equipment.

Moreover, numerical simulation results of our group (Naxakis et al., 2016a), based on the Alternative Transients Program – Electromagnetic Transients Program (ATP – EMTP) ATP-EMTP, 2015, have shown that potential over-voltages that may occur on lightning protection systems of PV installations can rise up to 150 kV. It is obvious that, conventional SPDs used in most PV installations (Kokkinos et al., 2012; Wang et al., 2011; Pons and Tommasini, 2013; Lightning and protection for rooftop photovoltaic systems (white paper), 2015; Lightning and Surge protection for free field power plants (white paper), 2015; Common Practices for Protection against the Effects of Lightning on Stand-Alone Photovoltaic Systems, 2003; Amicucci et al., 2012) will not be able to prevent such strong surges from propagating towards the PV modules. Motivating from such possible extreme cases, and taking into account the lack of data in the literature, we present herein results on lightning tests on PV module at voltage levels much higher than those imposed by the actual International Standards.

The results suggest that, neither power nor mechanical degradation is induced on the single-crystalline silicon photovoltaic module for voltages up to the limits imposed by Standards (i.e. 12 kV peak). In the range of our experiments, the module withstands lightning impulse voltages up to 35 kV peak, as far as the rest procedure of the Standards is strictly followed. Finally, a "rod-to-module" gap is used to simulate direct lightning strikes, showing that a voltage as high as 144 kV (peak) is necessary for destructing the module. Apart from the present introduction (Section 1), the article is constructed as follows:

- the experimental setup, the devices and materials used, and an extended evaluation of the measuring accuracy, are all together presented in Section 2;
- the results are presented and discussed in Section 3, for three different cases (i.e. "Tests According to IEC 61730-2", "Tests According to IEC 61730-2 except that $12 < V_p \leq 35$ kV", and "Direct Lightning Strike Test");
- conclusions are summarized in the last Section 4.

2. Experimental setup and accuracy tests

The entire work is realized in the indoor and outdoor facilities (Fig. 1) of the High Voltage Laboratory of the University of Patras, Greece (38°17′18.5″N 21°47′21.8″E). Standard 1.2/50 μs lightning impulse voltages (IEC 60060-1 IEC 60060-1, 2010) are produced by means of a Haefely Test AG impulse generator (Fig. 1(a)).

The generated voltage is monitored through a capacitive divider on a broadband digital oscilloscope (Tektronix DPO4104; 1 GHz/5 GS s^{-1}) which meets IEC 1180-2 (IEC 1180-2, 1994). Typical oscillogram of the test impulse voltages used here is given in Fig. 2.

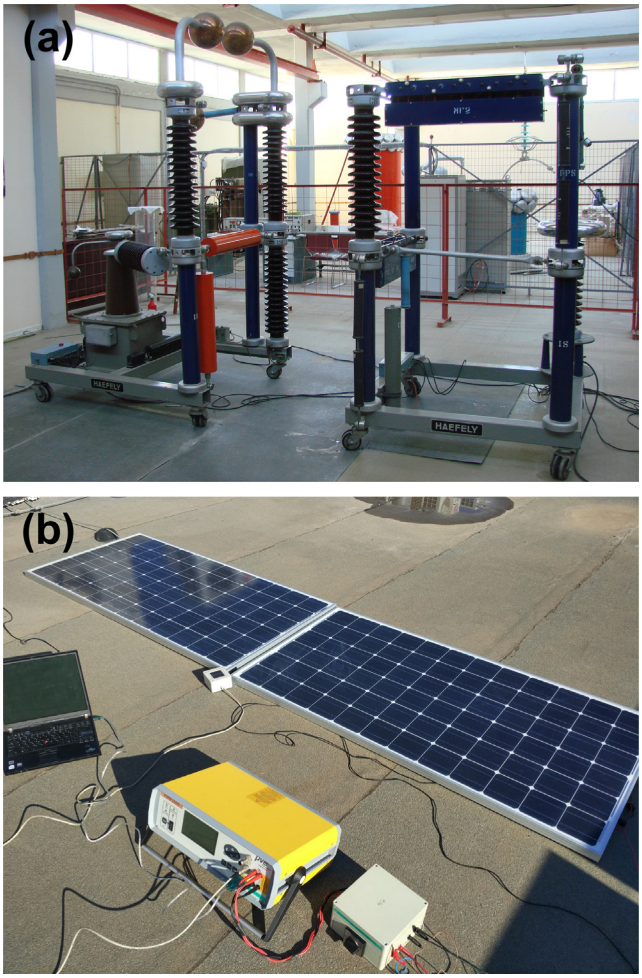

Fig. 1. (a) View of the indoor impulse generator employed in the present study. (b) Arrangement of the outdoor setup employed for I-V characterization of the PV modules.

PV modules are characterized with a peak power measuring and I-V tracer device (PVPM 2540C; 250 V/40 A; IEC 60904 (IEC 60904-3, 2008); Fig. 1(b)). The device is equipped with a platinum resis-

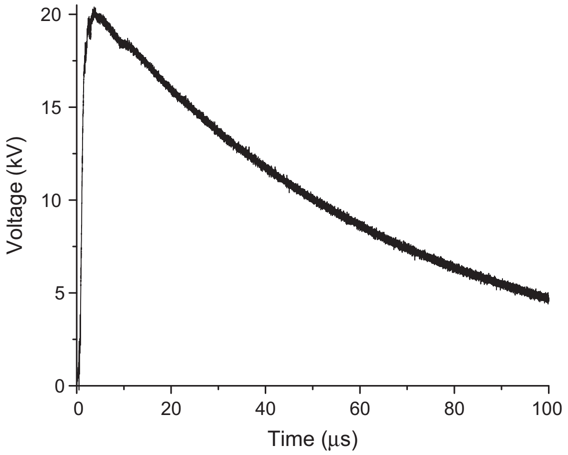

Fig. 2. Typical oscillogram of the standard lightning (1.2/50 μs) impulse voltage (here 20 kV peak) generated for the PV module tests.

tance temperature sensor (Class A Pt1000; IEC 60751 (IEC 60751, 2008) providing the ambient and PV module temperature, and as well with a silicon solar radiation sensor (SOZ-03) providing the irradiance value (G; W m^{-2}). Inherent measuring errors are discussed below.

For direct comparison reasons, all measurements are corrected to the Standard Test Conditions (STC; 25 °C/1000 W m^{-2}) by applying the following formulas in accordance to IEC 60891 (Correction Procedure 1) (IEC 60891, 2009).

$$I_{STC} = I_{measured} + I_{SC}\left(\frac{G_{STC}}{G_{measured}} - 1\right) + \alpha\left(T_{STC} - T_{measured}\right) \tag{1}$$

$$V_{STC} = V_{measured} - R_S(I_{STC} - I_{measured}) - \kappa I_{STC}(T_{STC} - T_{measured}) + \beta(T_{STC} - T_{measured}) \tag{2}$$

The indexes "measured" and "STC" under I, V, G, and T correspond to "measured" and "standard test conditions", respectively. I_{SC} is the measured short-circuit current of the test specimen at $G_{measured}$ and $T_{measured}$. α and β are the current and voltage temperature coefficients of the test specimen for the correction to STC. R_S is the internal series resistance of the test specimen and κ is a curve correction factor. The R_S is calculated at 0.9 Ω for every set of measurements based on the regulation IEC 60891 (IEC 60891, 2009), while κ is considered equal to 1.25×10^{-3} Ω °C^{-1} which is typical value for crystalline silicon cells (IEC 60891 IEC 60891, 2009).

Three PV modules are employed:

- "Module A"; it is a Luxor ECO LINE LX-200M module made of single-crystalline silicon cells (see Table 1 for features) and it is the test specimen.
- "Module A_{ref}"; it is a Luxor ECO LINE LX-200M module made of single-crystalline silicon cells (see Table 1 for features) and it is the "reference-control" module which is never stressed.
- "Module B"; it is a Luxor ECO LINE LX-195M module made of single-crystalline silicon cells (see Table 1 for features) and it is the specimen for direct strike tests. It has practically the same characteristics with modules "A" and "A_{ref}" (see Table 1) and it is used as an available one in our Laboratory for destructive tests.

Module A is prepared and tested in accordance to IEC 61730-2 Standard (Impulse voltage test MST 14). Then, tests on Module A are continued based on IEC 61730-2 by exceeding its higher voltage limits (12 kV < $V_p \leq$ 35 kV). Module B is neither prepared nor tested according to Standards, but it is used for direct lightning strike simulation experiments. Thus, the frame of the Module B is grounded directly and a positively-stressed rod (12 mm in diameter and 1.5 mm curvature radius) is placed 25 cm above it facing its center. Apart from the electrical characterization of module B, thermal studies are contacted by means of infrared camera (Fluke Ti32 Thermal Imager).

Table 1
Features of the Module studied, according to manufacturer (Luxor eco line, 2016).

Electrical data	LX-200M (A, A_{ref})	LX-195M (B)
Maximum power, $P_{max,STC}$ [W_p]	200	195
$P_{max,STC}$ Range	201.50–206.49	196.50–201.49
Maximum current, I_{max} [A]	5.39	5.33
Maximum voltage, V_{max} [V]	37.39	36.87
Short circuit current, I_{SC} [A]	5.87	5.79
Open circuit voltage, V_{OC} [V]	44.27	44.04
Efficiency at STC	15.79%	15.39%
Efficiency at 200 W/m^2	15.39%	15.00%
NOCT [°C]	47 ± 2 °C	47 ± 2 °C
Maximum systems voltage	1000 V	1000 V

Special attention is paid on taking into account any potential measuring uncertainty due to inherent tolerances of both the as-purchased modules and PVPM device. These errors are obviously independent of us. Thus, according to the manufacturer (Luxor eco line, 2016), the PV module specifications and average values can vary slightly, i.e. rated power ±3% and other values (see Table 1) ±10%. In addition, according to the PVPM manufacturer (PVPM, 2016), the peak power results have an accuracy of ±5% relating to the actual peak power value of the module under test. In any case, numerous reports (Hishikawa et al., 2016; Ueda et al., 2010; Jahn et al., 2012; Kimber, 2009) confirm inherent uncertainty during outdoor PV characterization up to 10%. Last but not least, according to systematic studies (Priya et al., 2015; Abella and Chenlo, 2011; Tsuno and Hishikawa, 2012; Duck et al., 2014; Vemula et al., 2013; Poissant et al., 2008), Eqs. (1) and (2) (as borrowed from IEC 60891 (IEC 60891, 2009) introduce inherent errors (up to 8%) depending on the irradiance and the PV module fabrication technology. Accordingly, numerous series of tests were realized for finding out the actual range of the inherent errors involved in our measurements. Indicative results are given in Fig. 3.

In this figure, I-V and P-V curves recorded under different sequences over time, are presented, all reduced to STC for direct comparison. In this figure, raw data are used for reliable comparison, i.e. data processing referred in NOTE 1 of IEC 60891 (IEC 60891, 2009) is not applied (NOTE 1: *As the data point V_{OC1} will be shifted off the current axis when translating from lower to higher irradiance, the translated V_{OC2} has to be determined by linear extrapolation from at least 3 data points near and below V_{OC1} or the original IV curve has to be measured sufficiently far beyond V_{OC1}*). Obviously, any deviation between the curves, lies well within the tolerance limits discussed above, and it is not related to the experimental procedure. This becomes clearer if curves obtained within narrow time intervals are compared (Fig. 3(a) and (b)). In any case, in the present study inherent errors affect the results up to ±5% and any deviation within this limit is hereafter neglected.

3. Results and discussion

3.1. Tests according to IEC 61730-2 ($V_p \leq 12$ kV)

Typical I-V and P-V curves obtained during Module A tests in full accordance to IEC 61730-2, are given in Fig. 4 (similar results, not shown here, are obtained for 12 kV, or even higher voltages; see Section 3.2). These curves are juxtaposed with the corresponding curves of Module A_{ref}, as they were acquired with a delay of a few seconds (see insets in subfigures of Fig. 4). Taking into account the measuring uncertainty discussed above, there is not any obvious electrical degradation of Module A. Furthermore, observations on the recorded oscillograms of the applied impulse voltage, did not depict any waveform distortion which could be a footprint of electrical breakdown (see Sections 3.2 and 3.3). Finally, rigorous inspection by naked eye of the module did not give any sign of mechanical degradation.

3.2. Tests according to IEC 61730-2 except that 12 < $V_p \leq 35$ kV

Motivating by our willing to get an idea about the safety factor resulting by the IEC 61730-2 application to our PV modules, the test voltage was increased up to about three times in respect to the limit set by Standard (12 kV versus 35 kV applied here). Typical I-V and P-V curves are given in Fig. 5.

Module A not only does not fail under this high stress, but it does not exhibit any electrical degradation as compared to the

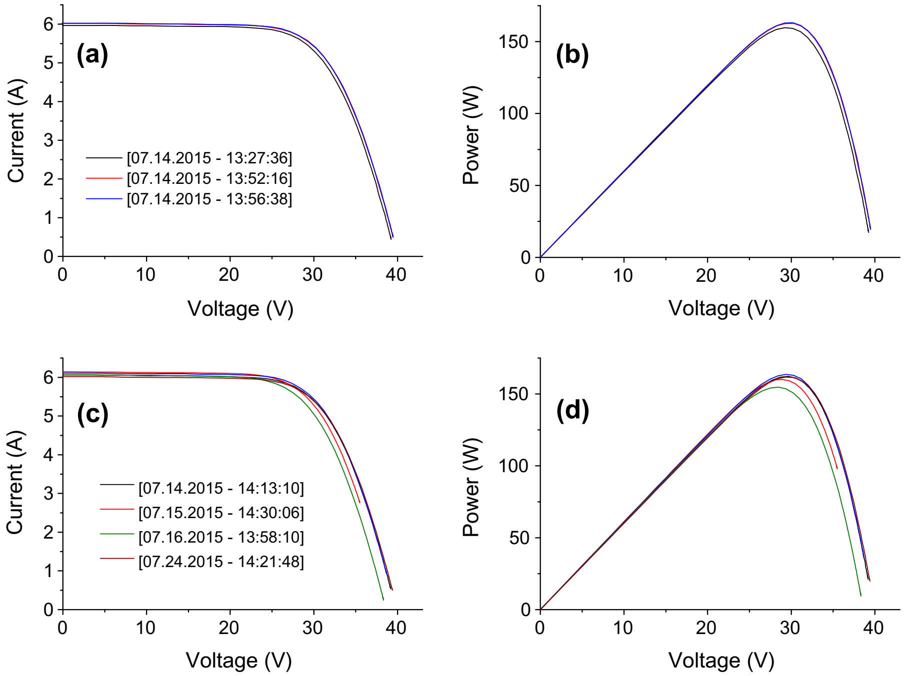

Fig. 3. I-V curves of the reference module Aref (corrected at STC), as received at successive moments over 30 min (a) and at different days around the same hour (c). The corresponding P-V curves are given as well ((b) and (d), respectively). See text for further description.

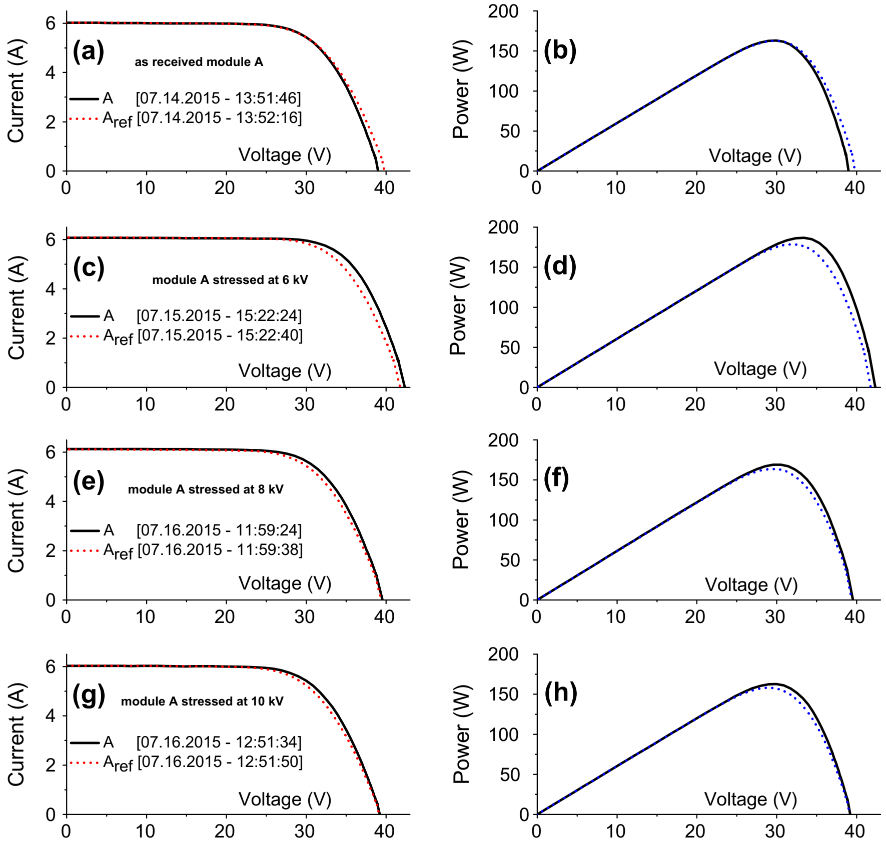

Fig. 4. I-V (left column) and P-V (right column) curves (corrected at STC) for module A: module as received (a and b), and stressed at 6 kV (c and d), 8 kV (e and f), and 10 kV (g and h). In any case, measurements on the reference module Aref are realized for evaluating any degradation of module A. The procedure meets the IEC 61730-2 Standard. Similar results, showing the withstanding of the module, have been obtained for 12 kV (not shown here) or even higher voltages, exceeding the IEC 61730-2 limits (see Fig. 5). Insets provide the exact acquisition date and time.

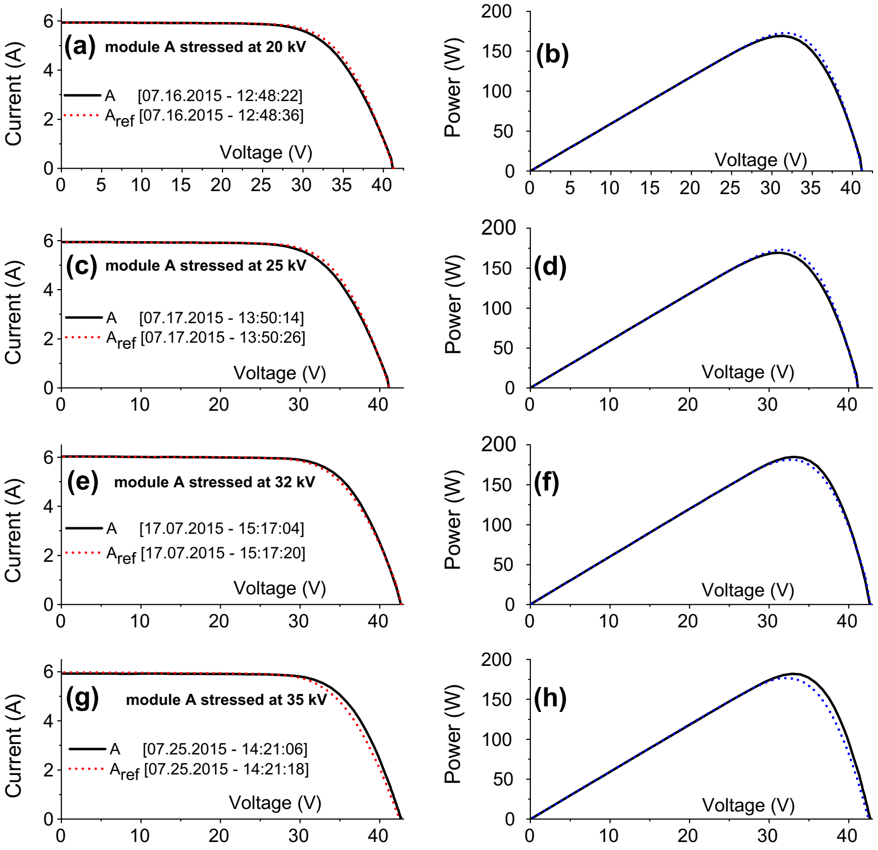

Fig. 5. Extreme tests. I-V (left column) and P-V (right column) curves (corrected at STC) for module A: stressed at 20 kV (a and b), 25 kV (c and d), 32 kV (e and f), and 35 kV (g and h). In any case, measurements on the reference module Aref are realized for evaluating any degradation of module A. The procedure meets all the steps of the IEC 61730-2 Standard, except the voltage levels which exceed those imposed by the IEC Standard. Insets provide the exact acquisition date and time.

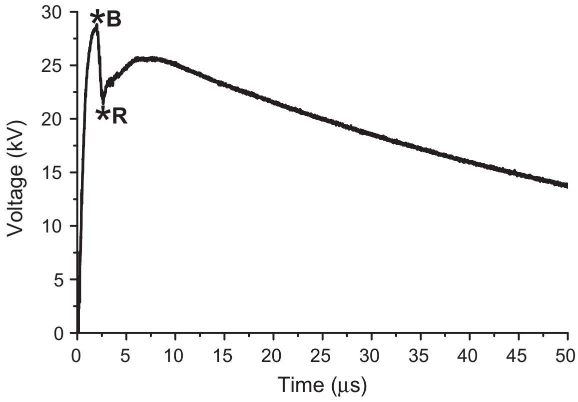

Fig. 6. Indicative oscillogram of the voltage across the PV module isolation during test at voltage level 28.5 kV, i.e. higher than those imposed by the Standard IEC 61730-2 (the rest procedure is according to the Standard). Isolation temporary breakdown and recovery are noted by B and R, respectively.

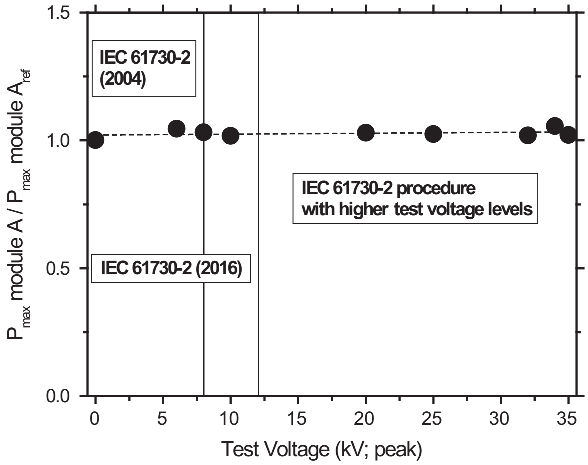

Fig. 7. Ratio between the maximum power value (Pmax) of Module A and the corresponding value of Module Aref over the entire range of the test voltage applied in this work; IEC Standard ranges are distinguished for comparison. The linear fitting of the experimental data indicates a constant ratio equal to 1 or, equivalently, absence of module electrical degradation. For any minor deviation of the ratio from value 1, see discussion in the last part of Section 2 and Table 1.

Module A_{ref}. Despite these macroscopic observations, voltage waveforms for V_p around 30 kV do imply overstressing of the module isolation. Indicatively, Fig. 6 gives an example of an oscillogram of the impulse voltage associated with partial breakdown of the module isolation (point B), which however recovers (point R) within 0.5 μs and does not lead to permanent failure.

Additionally, I-V curves and naked eye observations did not suggest any material degradation, similar to the results of Section 3.1. Summarizing the results of Sections 3.1 and 3.2, Fig. 7 shows the ratio between the maximum power value (P_{max}) of Module A to the corresponding value of Module A_{ref} over the entire range of the test voltage applied in this work. The ratio is

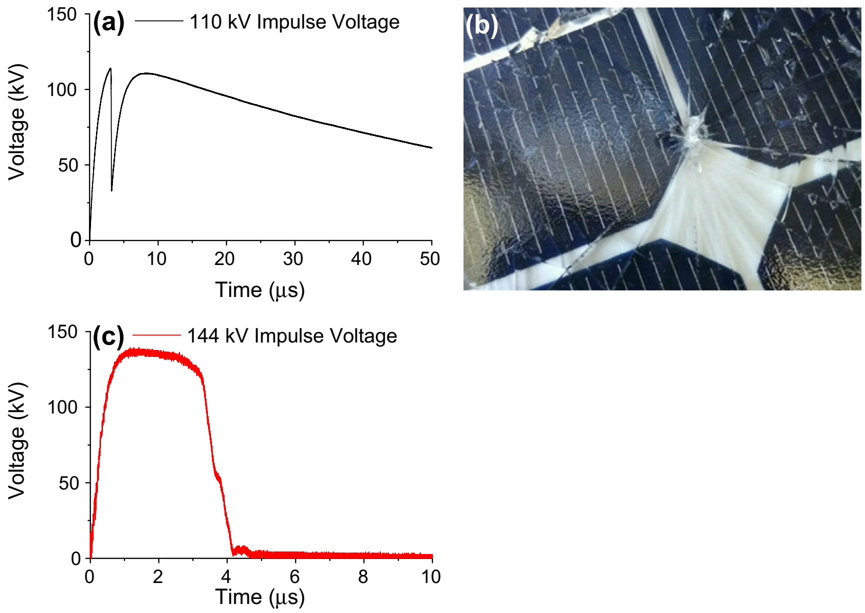

Fig. 8. Rod-to-module configuration for studying direct lightning strikes on the Module B. (a) Example of the gap voltage during non-destructive breakdown at 110 kV. (b) Broken Module B following destructive breakdown at 144 kV. (c) Gap voltage during Module B breakdown (case (b)).

constantly equal to ~1, supporting our statement for absence of module degradation (see the last part of Section 2 for possible reasons of any minor deviation from the value 1).

3.3. Direct lightning strike test (rod-to-module gap)

Apart from the aforementioned tests where the output terminals of the module were shorted and connected to the positive terminal of the impulse voltage generator, we carried out tests simulating direct lightning strikes on the module (see experimental details in Section 2). Tests with a "rod-to-module" configuration are justified taking into account that lightning strikes might be attracted by photovoltaic modules bypassing adjacent constructions (Sekioka, 2012). Towards this direction, Module B was successively stressed 50 times at 110 kV and 50 times at 120 kV. During these tests, air gap breakdowns (rod-frame) or surface breakdowns (rod-module surface-frame) were observed (for instance, see voltage drop on the oscillogram of (Fig. 8(a)), without however any mechanical damage of the PV module. The module was broken (Fig. 8(b)) when the testing voltage was increased at 144 kV peak and full breakdown was observed (Fig. 8(c)).

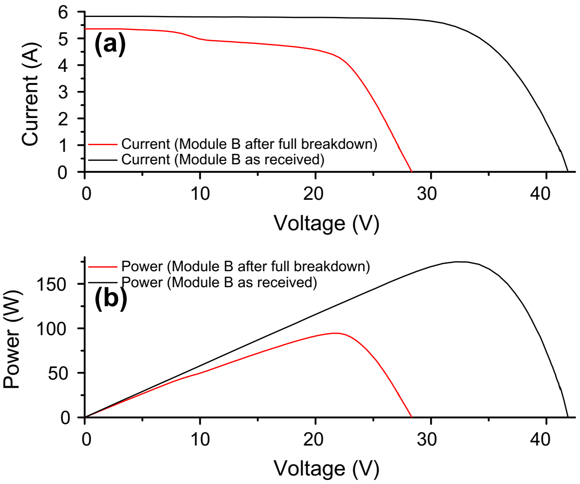

Fig. 9. Module B electrical degradation following its destructive breakdown during direct lightning strike tests (rod-to-module gap). (a) I-V characteristic curves before and after the breakdown (STC). (b) P-V characteristic curves before and after the breakdown (STC).

Table 2
Comparison of the Module B features before and after its breakdown.

Electrical data	STC reduced (after)	STC reduced (before)
Maximum power, $P_{max,STC}$ [W_p]	94.7	174.56
Maximum current, I_{max} [A]	4.39	5.26
Maximum voltage, V_{max} [V]	21.5	33.17
Short circuit current, I_{SC} [A]	5.35	5.82
Open circuit voltage, V_{OC} [V]	28.32	41.88
Series resistance, R_s [Ohm]	3.0	0.9
Parallel resistance, R_p [Ohm]	61.0	472.3
Fil Factor, FF [%]	62.1	72.3
Irradiance, E_{eff} [W/m^2]	1000	1000
Modules temp, T_{mod} [°C]	25	25

Fig. 9 clarifies the electrical degradation of the Module B, following the full breakdown (bypass diodes in the junction box of the module were activated). Although the module is practically useless, Table 2 compares the values of the main features of Module B before and after the breakdown. The module is still operational but obviously highly degraded.

Finally, Fig. 10 unveils that the broken module appears random distribution of the temperature over it surface. In this figure, Module B terminals are shorted (I_{SC} thus flows) and temperature pattern over the module surface is recorded by infrared images. Results from line profile analyses, in terms of the temperature reduced to the maximum one on each module, presents uniform thermal distribution before breakdown (Fig. 10(a)), which is strongly disturbed after breakdown, especially within the area of the destructive strike termination (Fig. 10(b)).

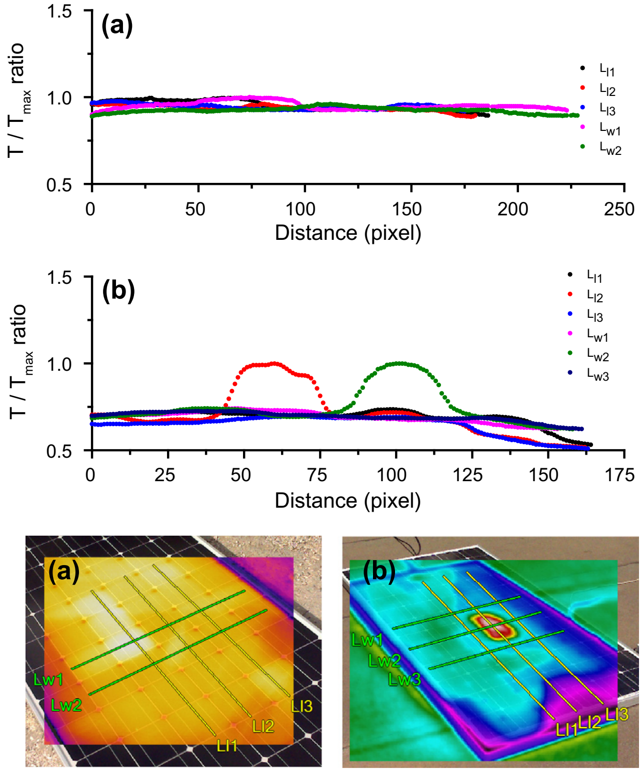

Fig. 10. Line profile curves, due to infrared images, over the surface of the Module B before (a) and after (b) its full breakdown. The temperature is reduced to the maximum one for faire comparison of the thermal distribution along selected lines in both cases (before and after). The infrared images are superimposed to visible ones for providing an idea of the probed area dimensions.

4. Conclusions

Single-crystalline silicon photovoltaic modules were tested under lightning impulse voltages, taking into account most of the experimental uncertainty factors. The test referred to peak voltage level up to 12 kV (according to the recently, 2016, revised IEC 61730-2 Standard) and up to 35 kV, i.e. about three times higher than the maximum value imposed by the above Standard (keeping the rest testing procedure in accordance to the Standard). Furthermore, a rod-to-module gap was stressed for experiments simulating direct lightning strikes on modules (impulse voltage level: 110 kV to 144 kV peak). In the light of the present experiments, the modules that were prepared according to IEC 61730-2 withstood all voltage levels and their I-V characteristic curves did not imply any degradation. Module subjected to direct strikes did not appear obvious degradation as far as the voltage was lower than about 144 kV peak. Thereafter, the module was completely destroyed (broken), electrically degraded highly, and appeared random thermal distribution on its surface with the highest temperature measured within the area of the destructive strike termination. The present work intends to contribute in providing experimental data for improved designs of photovoltaic module protection systems, and consists part of an ongoing research.

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