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Tests of Lightning Withstand Capability of PV-Systems and Measurements of Induced Voltages at a Model of a PV-System with ZnO-Surge-Arresters

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ABSTRACT

PV-modules on roofs of buidings are exposed to lightning stokes. On the new building of ISB's department of electrical engineering the PV-laboratory will get in 1993 a 60kW PV-generator, which will be used for research on PV-inverters and PV-systems. As no informations about sensitivity of solar cells, modules and systems to lightning strokes and their electromagnetic field were available, we decided to make extended tests in our high voltage laboratory. We hoped to learn as much as possible about optimum protection of such an installation against lightning. Practical work was done mainly by graduating students. Most interesting results of these tests are presented in this paper.

1. High Impulse Current Generator

In a first step, our high impulse-voltage generator had to be changed into a high impulse-current generator. It was equipped at first with 6 and in summer 1991 with 10 capacitors of 1,2µF/50kV each. As we expected damages in PV-modules mainly from high di/dt and maximum current Ipeak, we tried to get high values for these two important parameters by using a coaxial layout with low inductance. It was optimised for delivering high impulse currents with short rise times into metallic frames (maximum length about 50cm) of photovoltaic modules (see fig. 1 and 2). Highest values ever reached were Ipeak = 108kA and di/dt = 53kA/µs. These values are beyond the values of most lightning currents. However, due to budget limitations, we could not afford capacitors large enough to obtain typical values of lightning currents for electrical charge Q. Best values ever reached for Q are around 0,6As. It took a lot of time to optimise the measurement circuits (e.g. high current shunts, dividers, coaxial cables, matching problems and so on). Fig. 3 shows a typical impulse current delivered by our high current generator.

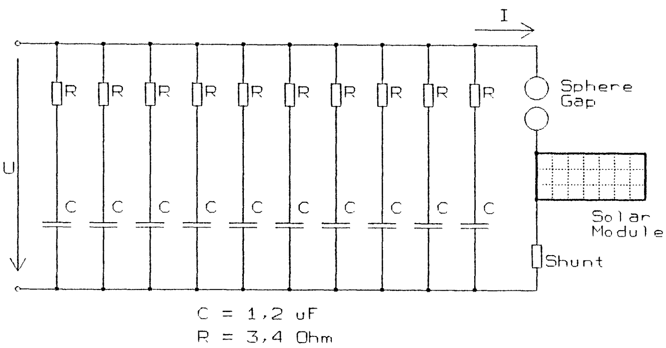

Fig. 1 : Schematic diagram of ISB's high impulse-current generator.

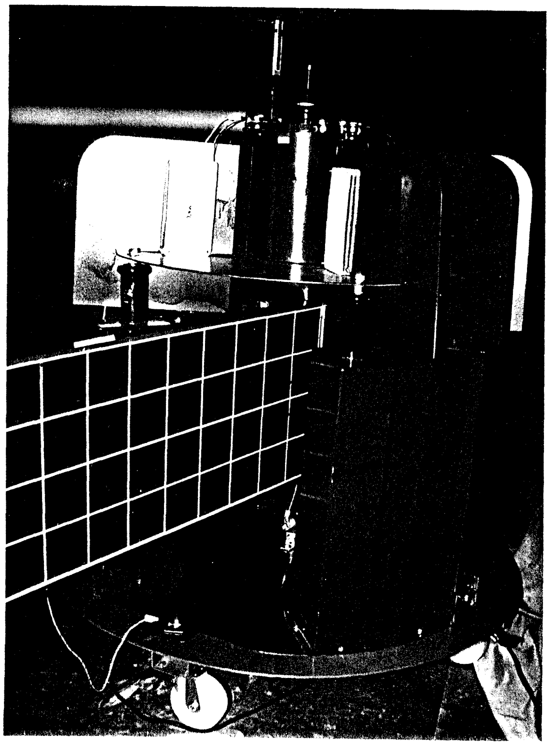

Fig. 2 : Photograph of ISB's high impulse-current generator.

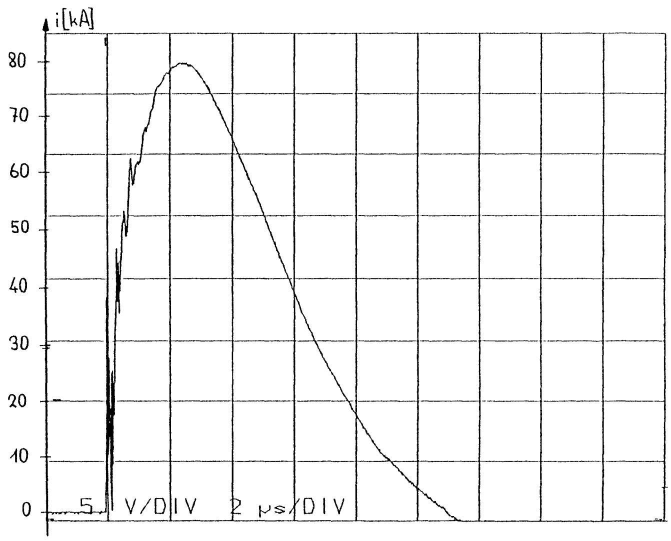

Fig. 3 : Typical high impulse-current produced by ISB's generator (I_{peak} = 80kA, di/dt = 53kA/µs).

2. Test Stand for I-V-Characteristics of Solar Modules

In order to make reproduceable relative measurements of I-V-characteristics of solar cells, a test stand with 30 fluorescent lamps was developped. The lamps are of a special type (BIOLUX made by OSRAM) and produce light with a spectrum quite similar to sunlight. With this apparatus it is possible to get a quite homogeneous irradiance (within a few %) of 300...400 W/m² (depending on the size of the module under test) in a rectangle about 130cm long and 50cm wide. With this test stand I-V-characteristics of PV-modules before and after exposure to simulated lightning currents were measured.

3. Tests with Solar Cells and stand-alone PV-Modules

A lot of tests were carried out at first with single cells, then with 3-cell-strips and finally with a few modules (mostly donated by general representatives in Switzerland). For the tests with single cells and 3-cell strips, the impulse current was flowing through a wire very close (1 to 4 mm) to the edge of the cell (see fig. 4). For the module tests the impulse current was injected either into the shorter edge (see fig. 1), into the center of the metallic frame (see fig. 5) or in case of a frameless module into a flat conductor right under the back foil of the module (see fig. 7). Thus we could simulate direct lightning strokes into the frame of the module or into the supporting structure of a frameless module.

Before our tests we expected damages due to direct breakdown between frame and solar cells in the module, causing a complete failure of the module. With high di/dt values of 40...50kA/µs inductive voltage along a metallic conductor (L' around 1 µH/m) is 40...50kV/m. However, we never observed such a event.

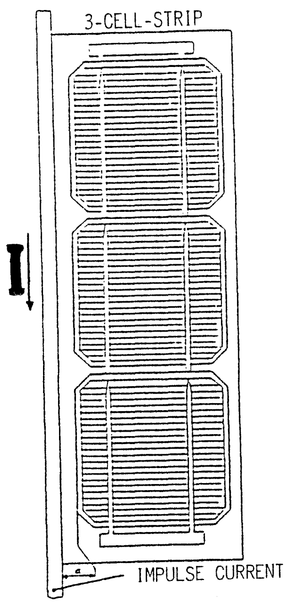

Fig. 4 : Arrangement for testing 3-cell-strips with high impulse-currents.

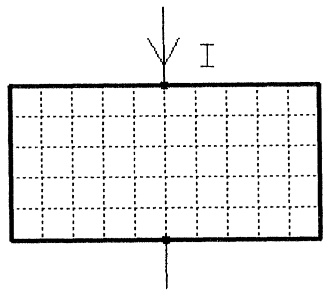

Fig. 5 : High impulse-current injected into center of module frame.

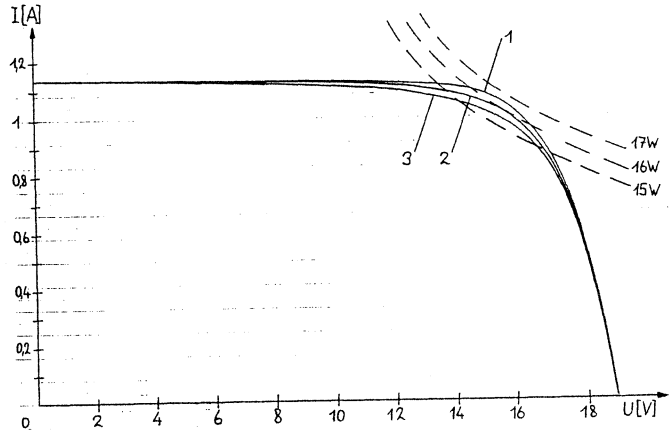

Fig. 6 : I-V-characteristics of module SOLAREX MSX60 at G' = 300W/m². Impulse-current feeding according to fig. 5, module shorted.
1: Initial characteristic
2: After impulse-current with I_{peak} = 53kA, di/dt = 33kA/µs.
3: After another impulse with I_{peak} = 80kA, di/dt = 53kA/µs.

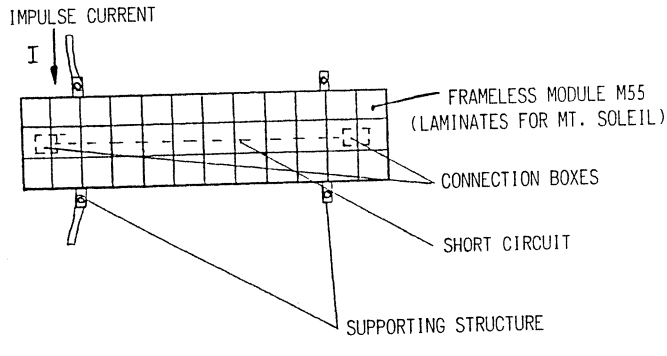

Fig. 7 : High impulse-current flowing through flat conductor right under frameless laminate M55 (shorted) made by Siemens Solar for Mont Soleil. Distance between conductor and cell: About 2mm.

The only effect of lightning currents flowing very close to solar cells proved to be a successive degradation of solar cell I-V-characteristic (especially a reduction of fill factor) as a result of the fast changing electromagnetic field of the currents (see fig. 6 and 8). Cells with considerable degradation of fill factor have also visible defects in the metallic grid on the front and back side, which may be caused by eddy currents in closed loops of the metallic grid (see fig. 9 and 10 for mono-cristalline cells made by Siemens Solar). Fig. 11 shows similar defects in the back contact of a polycristalline cell made by Telefunken Systemtechnik (no visible defect on front side, as there are no closed loops on the front grid).
The degradation of the I-V-characteristic is possibly not only caused by an increase of the series resistance due to damage in the front and back contacts but also due to defects in the internal structure of the semiconductor material caused by the electromagnetic field. Degradation of the I-V-characteristic of the whole cell proved to be caused mainly by a degradation of the cell area very close the lightning current.

The damage caused by lightning currents in the frame depends considerably on the design and layout of the module. Modules with smaller distances (1..2 mm) between frame and cells get more severe defects than modules with greater distances (e.g. 5mm). In addition eddy currents in a metallic foil on the back side attenuate considerably the fast changing electromagnetic field. Therefore they protect the solar cells right above this foil. Such metal foils may cause other problems, but in our tests they were a big advantage for the modules subject to magnetic fields of lightning currents. In a module made by Kyocera (LA361J48) with both favorable conditions, no degradation of the I-V-characteristic was observed even with the strongest current we could generate. Other modules made by Solarex (MSX60) and Siemens Solar (M20, M65) without such a foil and with a smaller distance between frame and cells showed I-V-degradations like those shown in fig. 6 and 8.

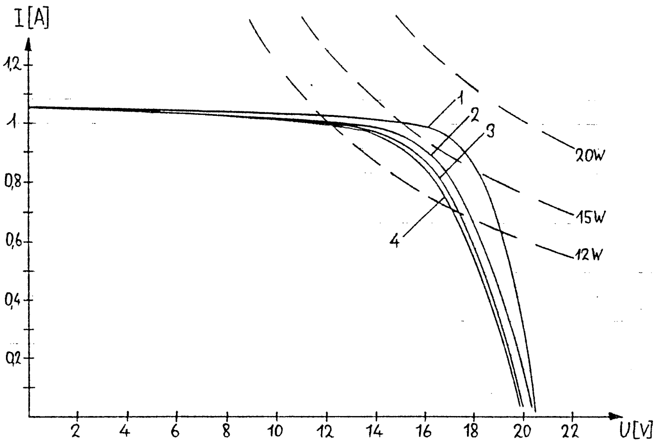

Fig. 8 : I-V-characteristic of frameless laminate M55 made by Siemens Solar for Mont Soleil at G' = 320 W/m². Impulse-current feeding according to fig. 7, module shorted.
1: Initial characteristic.
2: After impulse-current with I_{peak} = 53kA, di/dt = 33kA/µs.
3: After another impulse with I_{peak} = 69kA, di/dt = 43kA/µs.
4: After another impulse with I_{peak} = 80kA, di/dt = 53kA/µs.

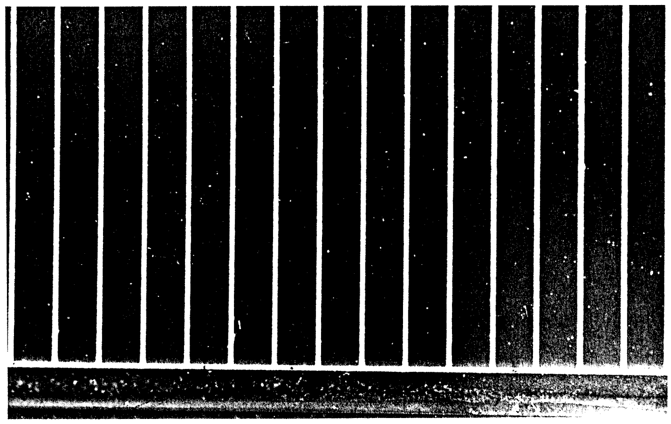

Fig. 9 : Defects in front grid of a monocristalline cell made by Siemens, caused by a high impulse-current.

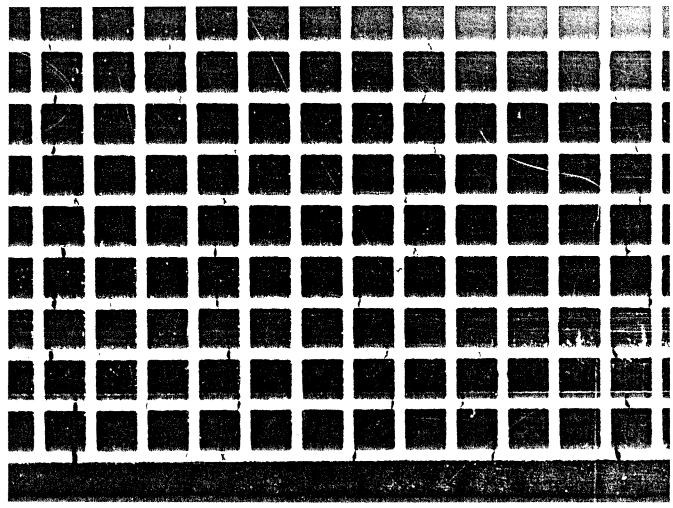

Fig. 10: Defects in back contact of a monocristalline cell made by Siemens, caused by a high-impulse-current

Fig. 11: Defects in back contact of a polycristalline cell made by Telefunken Systemtechnik, caused by high-impulse-current.

4. Tests with a Model of a PV-System

Damage caused by lightning currents depends also on the wiring of the module. We found that the same impulse current caused increased damage when the cells or modules were short-circuited than when they were not connected. Therefore the tests described in chapter 3 were carried out mostly with shorted modules.

We decided to make similar tests in a model of a whole PV-system consisting of a module with a lightning current in its frame, a short connection to a connection box with surge arresters to ground on both + and -, a shielded line of about 6m to a DC-power consumer (e.g. PV-inverter or battery) and a second set of surge arresters at the end of this line (see fig. 12). In order to get information about the effect of surge arresters on both sides of this line, voltage and current at the surge arresters on both sides of the lines were measured. Modules without internal bypass diodes were equipped with bypass diodes in the connection box for these tests.

Experiments with this model showed that damages in the wired modules were not worse than with short-circuited modules, even when the surge arresters started to conduct in moments of high di/dt in the front of the impulse currents. Modules with 3 parallel rows of 10 cells (Siemens M20 and M65) produced induced voltages that were not high enough to make the surge arresters (Dehn VM500) conduct. Tests with modules with 4 rows of 9 cells from Kyocera (LA361J48) with only a little larger area made them conduct. It seems that the internal wiring of 3-row-modules produces less induced voltage at the module terminals when a lightning current flows through the short side of the frame. Bypass diodes mounted directly at the terminals of a module with a single connection box (Kyocera LA361J48) were destroyed (short-circuit after test) already at medium lightning currents. In modules with built-in bypass diodes across 2/3 of the whole module string (e.g. Siemens Solar M65 and others) there were no defects in the bypass diodes. Probably the series impedance of the remaining 1/3 of the module string (10 cells in a M65) limited the current in the two bypass diodes to a safe level.

To judge the effect of surge arresters on both sides of the line without the influence of (slowly changing) module parameters a dummy module made of wire was used for most tests. Results obtained were confimed later with some tests with real modules. With this model the voltages induced were a little stronger than with real modules. By placing surge arresters on both sides, the current in the arrester on the inverter/battery side could be reduced considerably. In our test installation, arrester current at the end of a power line through a steel pipe with a diameter of 5cm and a length of about 6m was only about 30% of the current at the beginning of the line (see fig. 13 and 14). A shielded cable of 10m with the same conductor diameter (10mm²) and a copper shield of 10mm² had about the same effect. Use of an iron shielding pipe does not bring a big advantage. However, using surge arresters on both sides of a shielded power cable seems to be an efficient means to reduce transient voltages and currents into the input terminals of an inverter or charge controller of a battery system.

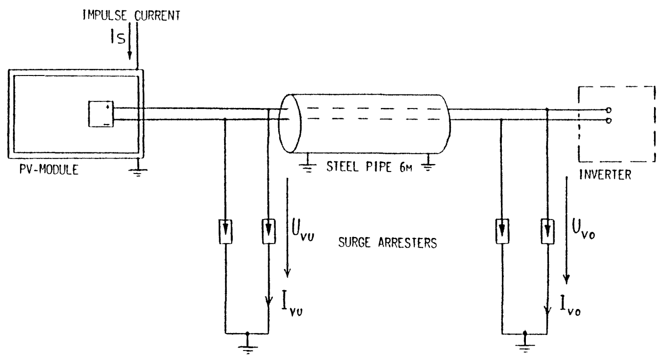

Fig. 12: Schematic diagram of our model of a PV-system.

Left : PV-module with high impulse-current flowing in its frame and two wires from connection box to surge arresters.

Center : Shielded power line from PV-module to DC-load going through a steel pipe about 6m long with a diameter of 5cm.

Right : Another set of surge arresters and simulated DC-load (not connected)

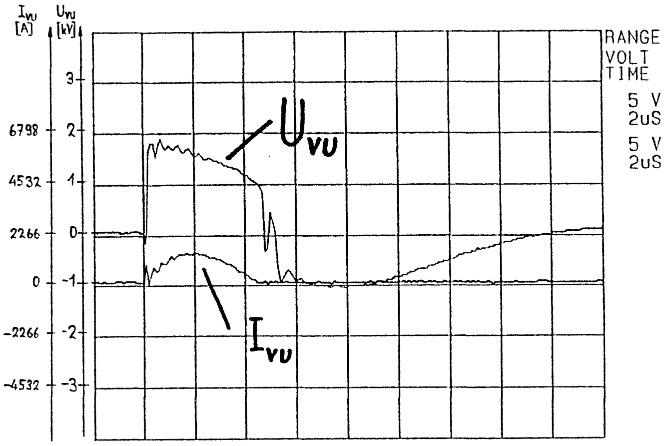

Fig. 13: Current I_{VU} and voltage U_{VU} at surge arrester close to PV-module-dummy (left side in fig.12) with high impulse-current flowing through its frame (I_{peak} = 108kA, di/dt = 40kA/µs).

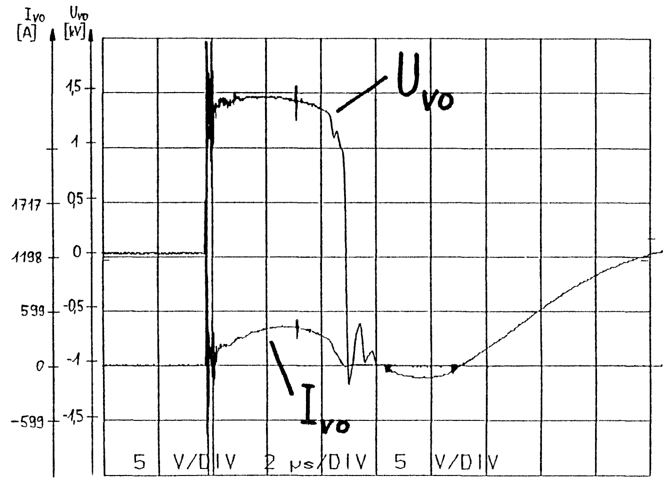

Fig. 14: Current I_{VO} and voltage U_{VO} at surge arrester after shielded power line close to DC-load (right side in fig. 12) under same conditions as in fig. 13.

ACKNOWLEDGEMENTS

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IMPORTANT NOTICE

REFERENCES (internal ISB-reports, in German):

- M. Boss, D. Ettlin: "EMV-Festigkeit von Photovoltaik-Systemen". Diplomarbeit 1992, ISB.
- M. Ingold, H.R. Röthlisberger: "EMV-Festigkeit von Solar-modulen". Diplomarbeit 1991, ISB.
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