SYSTEM DESIGN AND ASSESSMENT NOTES

NOTE 47

November 2016

EMP-HARDENED PHOTOVOLTAIC GENERATORS: A POSSIBLE EMERGENCY POWER SOLUTION FOR CRITICAL INFRASTRUCTURE?

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Abstract

One possible cause for a continental blackout of the electrical energy supply and the distribution grid might be a High altitude ElectroMagnetic Pulse (HEMP). In this event, a Photovoltaic (PV)-generator could be a possible local backup solution, provided it is immune to HEMP. In order to assess the EMP-immunity, both radiated and conducted high power electromagnetic environment (HPEM) threats – as mentioned in HPEM standards – have been applied on each component level of PV-generators, except the inverters, which are relatively easy to be protected by well-known protection measures. Extensive practical experiments proved that the HPEM immunity of individual PV-cells and PV-modules is much higher than commonly expected. PV-generators of any size consisting of a few or many PV-modules and its cabling can also be protected by reasonable protection measures to comply with highest electromagnetic protection requirements.

Keywords: HPEM, HEMP, PV-cell, PV-generators, grid, off-grid, infrastructure, protection

1 INTRODUCTION AND MOTIVATION

The most critical among all critical infrastructures is ELECTRICITY!

Renewable energy sources are becoming increasingly popular. Photovoltaic (PV)-generators, which convert sunlight into electricity, have become affordable in the past few years. Many PV-generators have already reached “grid-parity”, which means that their overall energy production cost became equal or even lower than electricity from the grid. With an increase of 34% in 2015, the total worldwide installed PV-power reached 256 GW at the end of the year. PV-generators produce decentralized renewable electricity and provide certain independence from the grid, especially in the case of off-grid systems, which are typically combined with local energy storage.

Some countries or regions already have a large number of small power PV-generators typically installed on roofs of private buildings, each generating a peak power of a few kW. In industrial areas there are also many medium power generators having peak powers of tens to hundreds of kW each. Often organizations which run critical infrastructure also use PV-generators, but they do not identify them as critical parts deserving protection against martial acts. However, off-grid PV-generators have a great potential to be used as a part of an independent emergency power system.

This raises the following questions: How vulnerable are PV-generator systems in the case of a high altitude electromagnetic pulse (HEMP) event? Can such a system be protected efficiently for the use as emergency power of critical infrastructure?

Recently an EMC-Consultant proposed to shield the PV-modules by a thin wire mesh, which is certainly not a very suitable option. The shield (wire mesh) partially obstructs the sunlight and therefore reduces the energy-conversion efficiency and simultaneously increases the overall costs. Before designing protection, the HPEM immunity of PV-generators has to be assessed. Then it will be possible to determine proper protection requirements for standardized HPEM environments. So far, only a few publications about EMC characteristics of PV-cells exist, although there are many lightning protection products for PV-generator systems available on the market. This fact gave the motivation to investigate the immunity of PV-cells and PV-modules of different technologies.

2 BASIC PRINCIPLES OF PV-GENERATORS

A single PV-cell (Figure 1) with the size of 156 x 156 mm^2 in full sunlight (radiated power of approx. 1000 W/m^2) generates an electric power of approx. 5W (0.6 V / 8 A per cell, or approximately 200 W/m^2). Electrically a PV-cell is a diode (pn-junction, Figure 2), which produces a voltage of 0.6 V and a current proportional to the exposed light. Typically 60 or 72 cells are connected in series to form a PV-module. A single PV-module generates a power of 200 to 300 W DC, typically at 36 V / 8 A. PV-modules are connected in series to form a string producing up to 1000 V DC. String power is fed into an inverter, which optimises electricity production using maximum power point tracking (MPPT) and converts DC into AC. The Immunity and protection of inverters were not considered in this study since well-known protection measures can be applied to protect them.

A typical PV-module consists of 3 groups (**Figure 3**). Each group consists of 20 or 24 cells electrically connected in series. The 3 groups are as well electrically connected in series (daisy chained). A junction box collects all group wires and provides connection to the next module or to the inverter. In addition, each group has a bypass-diode located in the junction box. The bypass-diode protects the group from too high reverse voltages in case of local shading of one or several cells. The bypass-diode is electrically anti-parallel to the cells in the string. **A typical home system** consists of 1 to a few 10’s of PV-modules connected in series to form one or two strings with a DC voltage up to 1000 V and ~10 kW peak power. Currents in a string are in the order of 10 A. The inverter converts DC to AC for coupling into the AC-grid. **Large scale PV-generators,** with a peak power of up to 100 MW, have 1000’s of modules, which are always divided into many strings consisting of 20 to 30 modules each. Each string is connected to an inverter.

Figure 1: Monocrystalline cell (left) and Polycrystalline cell (right)

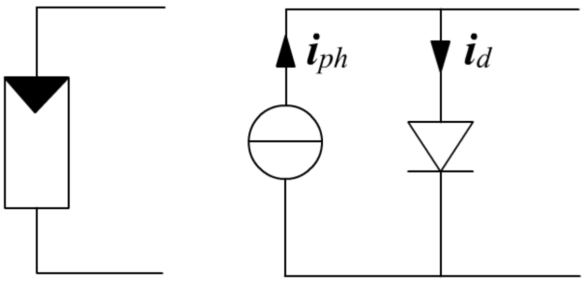


Figure 2: Schematic / Principle of PV-cells

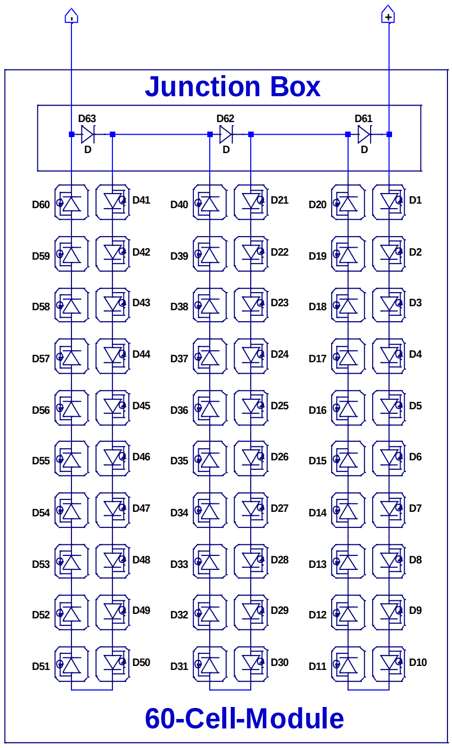


Figure 3: Electrical circuit of a module

3 DETERMINING THE DAMAGE LEVELS OF TYPICAL PV-COMPONENTS

3.1 Induced EMP-currents in a PV-module and its installation

In order to better understand the damage levels and safety margins of typical PV-components, such as PV-cells; bypass-diodes and PV-modules were investigated with regard to transient surge behaviour. A single PV-cell is a diode with a large pn-junction surface, which forms a relatively large capacitor. Often one side is fully metallized as an electrode. As a second electrode, a thin wire grid collects the current on the side which is directed towards the sunlight. Typically, a group of 10 to 12 cells, which are electrically connected in series, form a loop which is closed by a so called bypass-diode in reverse direction. The loop area is typically 0.3 x 1.5 m^2 = 0.45 m^2.

The bypass-diode protects the cells of this group in the case of partial shading. The energy fluence of HEMP is 114 mJ/m^2 [1]. Current induced in this loop depends on polarity, and flows either in forward or reverse direction through all diodes. Experiments with a wire model have shown that less than 100 A of peak current and less than 2 mJ of HEMP-energy are coupled into a single loop. A single PV-module consists of three loops, which are electrically in series. Experiments with a wire model (**Figure 4**) of such a PV-module have shown that less than 200 A of peak current and less than 4 mJ of HEMP-energy are coupled into a single module consisting of three groups.

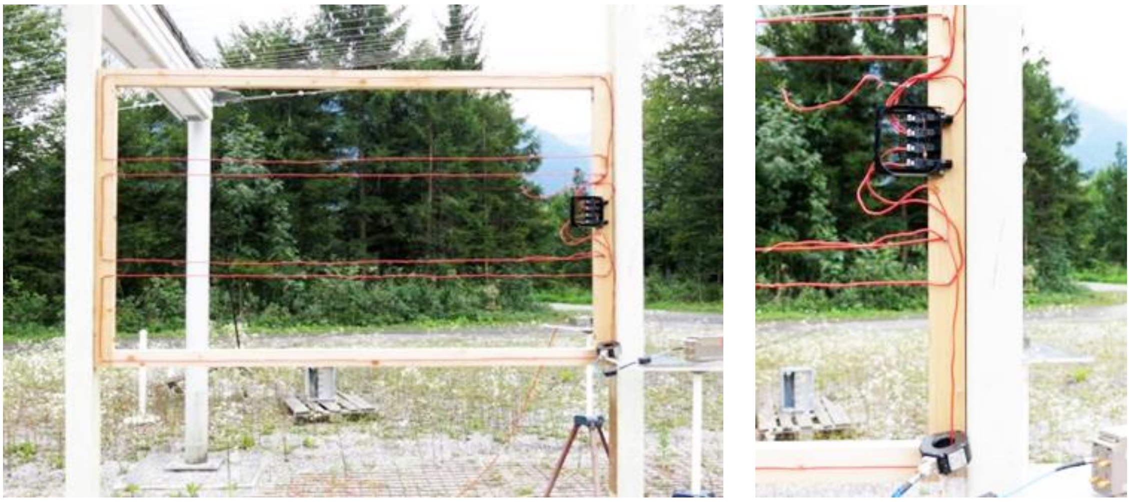


Figure 4: Wire model of module (left) and a single loop (right) in the HEMP simulator

However, there is also HEMP-coupling into the installation cables interconnecting the modules and the inverter that needs to be considered. Depending on the cable length and geometry, these early time HEMP (E1) currents can be as high as 2 kA. No coupling of intermediate time HEMP (E2) is expected because PV-generator cables are usually shorter than 100 m. PV-cell diodes in a loop and its bypass-diode are electrically anti-parallel. Therefore, externally coupled currents can always flow in forward direction, either through the cell diodes or through the bypass-diodes. This already provides some limited protection, without any additional measures on the module. Another experiment has shown that a metal frame, as is often used around PV-modules has a significant influence on the current wave shape. The frame reduces the amplitude by 20 to 50%. Therefore all following experiments were carried out without a metal frame, in order to represent a worst case testing.

3.2 Immunity of PV-components to conducted threats

As DUT's (Device Under Test), the following PV-components were available for experiments to assess the damage thresholds against conducted surges with various pulse shapes:

<u>PV-cells of different technologies:</u> Poly- and monocrystalline versions (ERSOL Blue Power, Black Power); Standard and Hetero-Junction technology (HJT, Meyer Burger); in glass-glass and glass-back-sheet technology; Standard, smart wire grid connection (SWCT, Meyer Burger); Interdigitated back contacts (SunPower® Maxeon).

<u>Bypass-Diodes:</u> SL1110 (Schottky diode); SL1515 (Schottky diode); SBR12U45LH (SMD Schottky diode); new technologies using active bypass-diodes with ultra-low forward voltage were not yet available at the time of the tests and were not considered.

<u>PV-modules:</u> a) 60-cell module with polycrystalline cells in 3 loops, 3 bypass-diodes; b) module with the same parameters but with monocrystalline cells; c) module with the same parameters but with monocrystalline HJT cells in SWCT.

I-V-Characteristics of bypass-diodes and single PV-cells (diodes as well) were measured in forward and reverse directions of the diode (**Figure 5**). This is an important measurement in order to observe any test related changes, and to determine partial failure of the components.

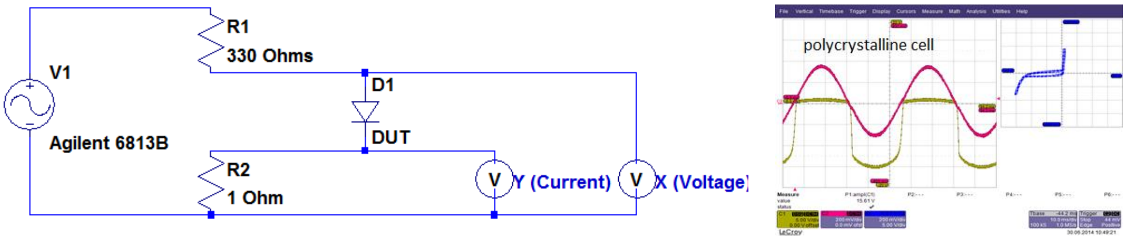


Figure 5: I-V Diode characteristic test scheme (left) and test result (right)

ElectroStatic Discharge (ESD) tests [2], both arc-discharge and direct contact method, were performed directly to the naked cell surface or the metal sheet, in order to test reactions to nanosecond rise time currents (Figure 6 left).

This is a brute-force method, as it usually does not happen in a PV-cell, which is typically embedded in a module between glass and plastic sheets. Several hundred ESD pulses up to 17 kV of both polarities – positive and negative – were randomly distributed over the surfaces of the cells.

Then a combination wave generator [3] with 2-ohm source impedance was used to generate surge currents of 8 µs risetime / 20 µs pulse width (8/20µs). The charging voltage was adjustable from 160V to 4kV, thus resulting in surge amplitudes from 80 A up to 2 kA. The surges were injected directly into the PV-cells or bypass-diodes, respectively. First, the tests in forward direction (Figure 6 right) were done with increasing amplitudes, starting from 80 A. The voltage across the cell during the surge was measured to observe any irregularity.

After each pulse, the cell was verified to have no damage by measuring and comparing I-V-characteristics. The surge amplitude was increased until the I-V-characteristics changed due to some damage, or up to 2kA, whichever was first. In the next step, the same test was repeated in reverse direction using new diodes or PV-cells, and starting from 80 A again.

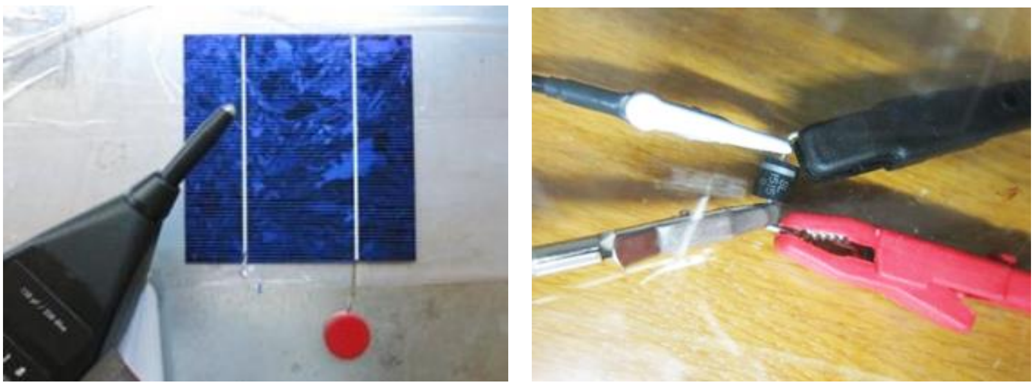


Figure 6: ESD on cell surface (left) and surge on a bypass-diode (right)

Finally HEMP-PCI-tests (Pulsed Current Injection) with currents from 1500 A up to 2.5 kA 20/500 ns were applied directly into new PV-cells and bypass-diodes. A current of 2500 A corresponds to the full conducted early-time HEMP-threat level required by MIL-STD-188-125 [4] for a single long wire. For this current injection the cells were laid between two copper sheets for full surface connection.

First, the current was injected in forward direction starting at 1500 A. The voltage across the cell was measured during the injection. After the pulse, the I-V-characteristics were measured and compared with pre-pulse results, to verify that the DUT was not damaged. Then the injected current amplitude was increased to 2500 A, and I-V-characteristics of the DUT were measured again to determine any damage. If there was any sign of damage, a new DUT of the same type was used and the procedure was repeated with injections in reverse direction.

4 TEST RESULTS

4.1 ESD tests directly on PV-cell surface

At least 30 positive and 30 negative polarity discharges, respectively forward and reverse 17k V ESD-discharges, of 10 mJ each were applied directly to the naked PV-cells, and randomly distributed over the cell surface.

Visually, it was observed that the arc discharge not only hit the metal fingers of the cell as expected, but also entered directly into the semiconductor between the metal fingers. Under the microscope, a slight colour change was observable directly at the entrance of the current into the semiconductor. Although the point discharge resulted in a relatively high current density at the point of impact, there was absolutely no noticeable change in the I-V-characteristics (see Figure 7 for the case of monocrystalline cell). No damage was observed in both forward and reverse directions for all tested PV-cells.

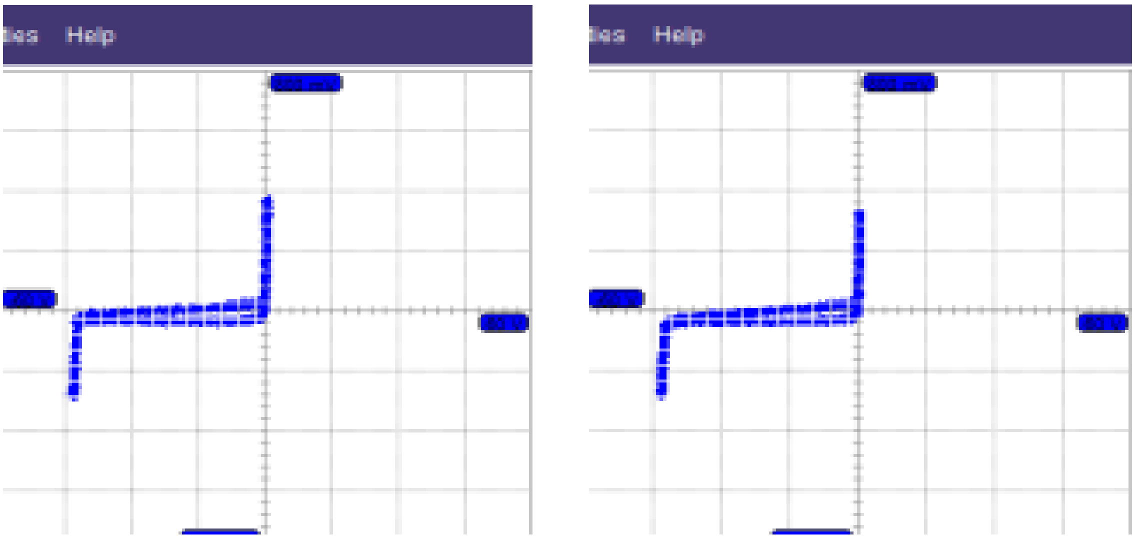


Figure 7: The I-V-characteristics of a monocrystalline PV-cell before (left) and after (right) a series of ESD discharges directly to the surface showed no changes and damages.

4.2 Surge tests on cells

Forward and reverse surge currents of the shape 8/20 μs and increasing levels of 80 A, 250 A, 500 A, 1000 A and 2000 A were injected into mono- and polycrystalline cells. In forward direction, no damage was observed for all test levels including 2000 A on both types of cells. Figure 7 shows the I-V-characteristic of a new polycrystalline cell and the same cell after a 2000 A surge in forward direction. The cell is not damaged.

After a surge current of 250 A in reverse direction, the monocrystalline cell first showed a reduced breakdown voltage in the I-V-characteristic. The same cell was then surged with 500 A, after which it was punctured and broken near the current entry point.

By feeding an external small DC-current into another unbroken cell that had been surged in reverse direction, the unequal current distribution in the cell can be seen easily using an infrared camera in a dark room. Another method is to take an IR picture of the cell without external load in sunlight. Figure 8 shows the punctured, locally damaged (resistive) PV-cell using both methods. It is assumed that the failure was caused by a too high current density in the avalanche breakdown mode. In principle the PV-cell is still working, but it has a lower efficiency, because some of the generated power is dissipated in a locally resistive part within the cell.

Figure 9 shows the I-V-characteristics of a polycrystalline cell before (left) and after (right) forward surge currents up to 2000A. There is no degradation.

A reverse surge current of 250 A into a polycrystalline cell caused some leakage, which was visible in the I–V-characteristic (see Figure 10 left). After increasing the reverse surge amplitude to 500 A a strong leakage resulted (see Figure 10 right).

HJT cells could withstand surge currents up to 1000 A in forward direction, and were therefore found to be somewhat more vulnerable to forward surges than mono- and polycrystalline cells, which showed no damage, even at 2000 A. However, HJT cells were found to be far more robust in reverse direction, as they could also withstand surge currents up to 1000 A in the reverse direction. Thus, the reverse surge immunity of mono- and polycrystalline cells is worse than that of the HJT cells, which withstand 1000 A in both reverse and forward directions. This is an interesting fact because reverse surge immunity seems to be the weakest point of PV components such as bypass diodes and PV-cells.

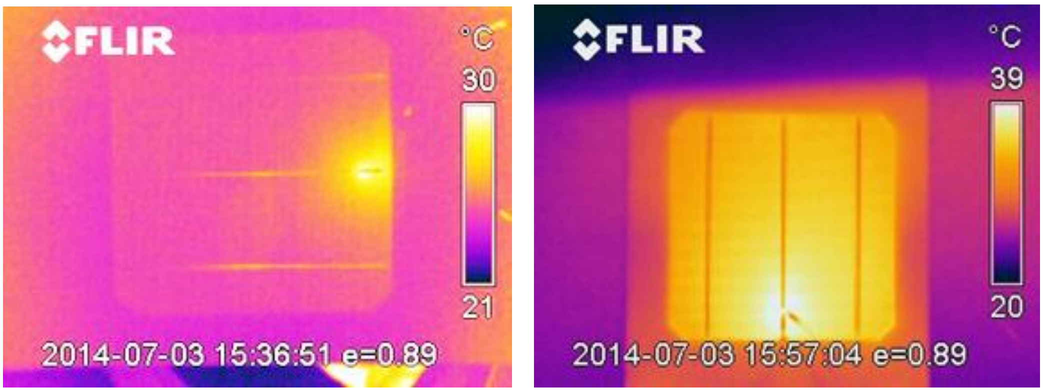


Figure 8: Current density on the broken monocrystalline cell using an external current of 0.1 A (left) and same active cell without load in sunlight (right).

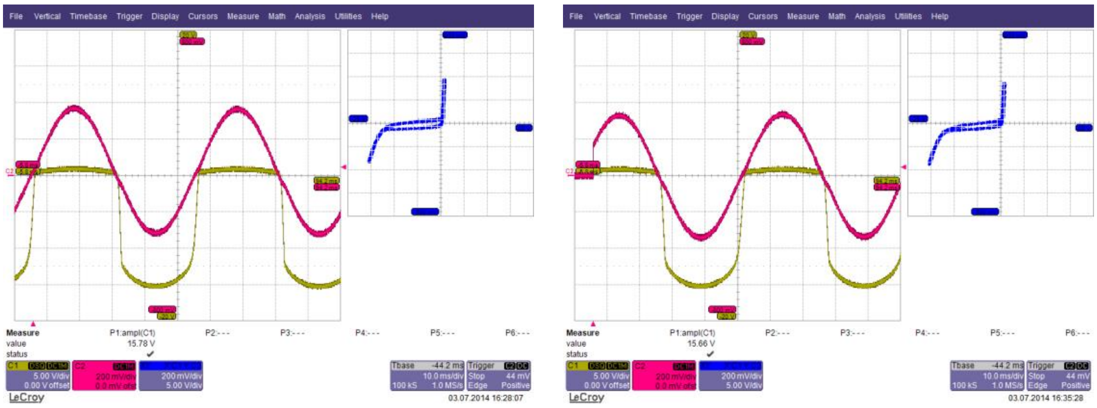


Figure 9: The I-V-Characteristic of a polycrystalline PV-cell before (left) and after 2000A surge in forward direction (right) shows no degradation.

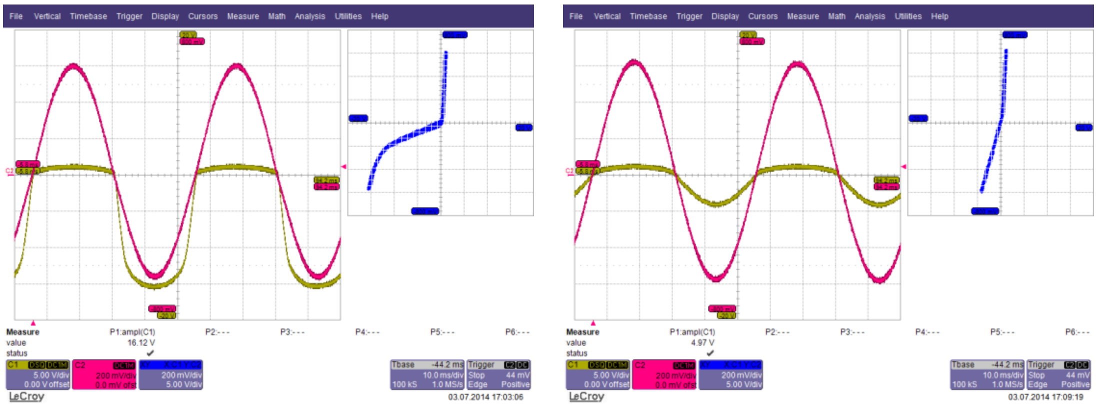


Figure 10: The I-V-Characteristic of a polycrystalline PV-cell shows some resistive leakage after a 250A surge in reverse direction (left). After a 500A surge in reverse direction the cell is damaged and behaves almost like a resistor (right).

4.3 Surge tests on bypass-diodes

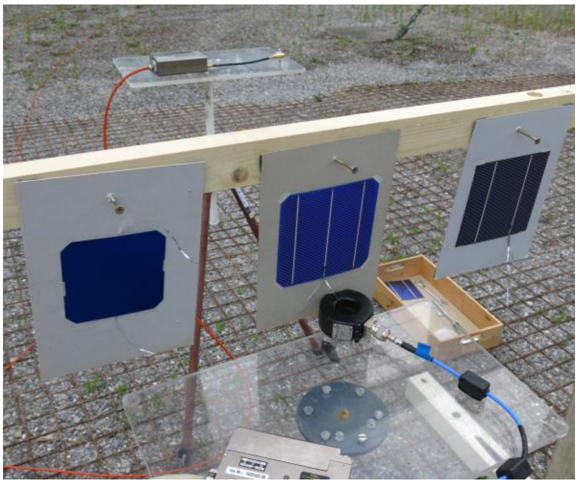
Schottky bypass-diodes SL1110 and SL1515 have easily survived all surges in forward direction up to 2000 A. However, in reverse direction surge currents of even less than 100 A (8/20 μs) permanently damaged the bypass-diodes. The bypass-diodes failed into short-circuits.

4.4 HEMP field tests

Individual PV-cells and four PV-modules with different cell technologies, different wiring and packaging were exposed to the full HEMP threat level (50 kV/m) [5] in the EMP-simulator VEPES (Figure 11). In a later test series, the DUT's were exposed to the double threat level (100 kV/m), and finally to the triple threat level (150 kV/m). All field tests were conducted in 6 different orientations (+/- x, +/- y, +/- z), and using three different loads in each orientation. As a nearly resistive load 3 Halogen bulbs of 12 V/35 W each were used in series. These lamps were also a good indicator to immediately signal the proper function of the modules before, during and after the EMP-pulse. All tests were also conducted with no load (open-circuit) and short-circuit of the module. At least 3 pulses per configuration and 3 field levels were fired. In total, more than 150 HEMP-pulses were applied per module.

No damage to any of the four PV-modules was observed in any of the above configurations. In two cases, one out of a total of 12 bypass-diodes failed into short-circuit during the 150 kV/m test after more than 100 cumulative HEMP-pulses.

This failure could not be repeated and it remains unclear whether this was a random or cumulative effect. The modules worked normally after replacing the defective bypass-diode.



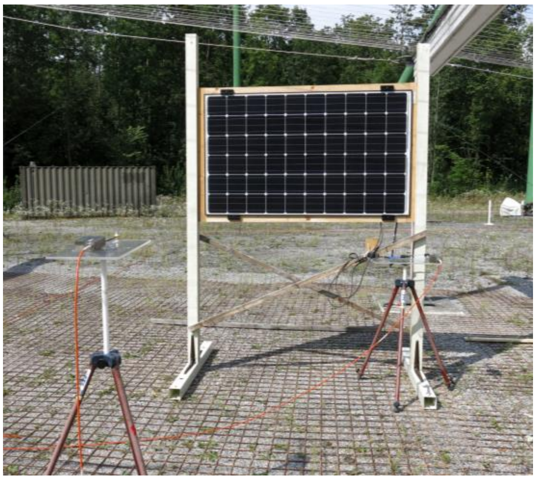


Figure 11: HEMP-field tests of different PV-cells (left) and of 60 cells PV-modules (right)

In the PV-module factory, the performance curve of all PV-modules was tested with the flasher, and compared to the power curve before the EMP-tests (see Figure 12). The flasher produces a standardised variable illumination to measure the power curve of PV-modules. Absolutely no alterations could be observed; all cells in the modules worked with the same power as before the HEMP-tests.

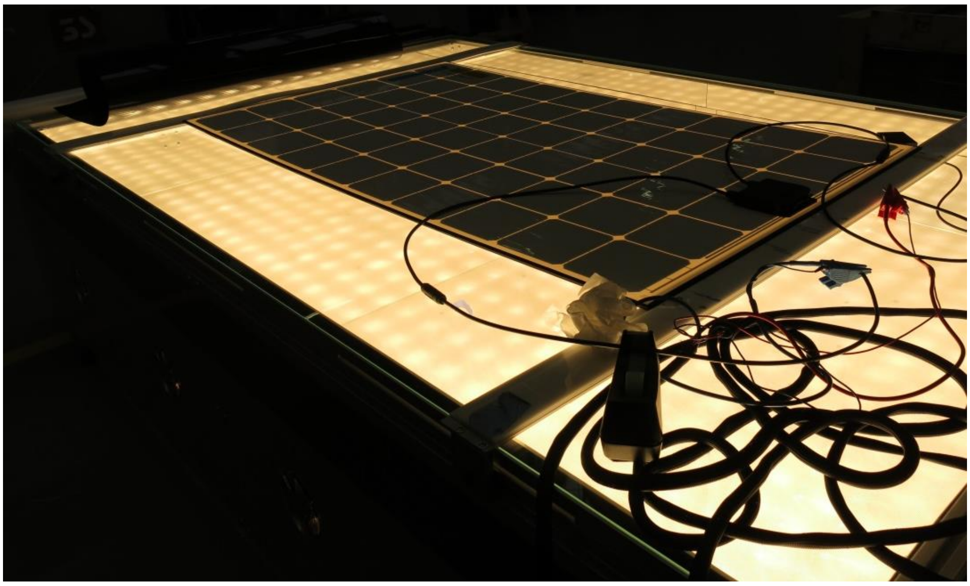


Figure 12: This flasher made by PASAN (the worldwide reference for measurement systems for modules and cells in the photovoltaic industry) is used to measure the performance curve of a PV-module before and after EMP-illumination tests.

5 COUPLING AND PROTECTION CONSIDERATIONS

In Swiss EMP-protected facilities, it is a common practise to use HPEM protection devices that combine lightning, HEMP and other transient protection. Such combined protection devices have an advantage, because they avoid the coordination problems of protection solutions with separate lightning and HEMP-protection.

Using a combined protection approach is also a cost and space saving solution. This is especially important for PV-generators, which are in most cases also exposed to direct lightning threats. If equipped with combined lightning and EMP-protection, PV-systems have the potential to become a well-hardened source of electrical energy, which could be of increasing importance for critical infrastructure in the future.

5.1 Coupling paths into PV-systems

The tests described in this paper have shown that PV-components have a rather high immunity against EMP-threats, and can easily survive more than full threat-level EMP-fields. However, if connected together to an extended system, we also have to consider coupling into the cabling.

The tests have also shown that most components can survive conducted HEMP-threats as expected from long cables. However, some components are quite sensitive to reverse surge currents, and therefore such reverse currents have to be avoided by adequate protection measures in the proper locations. First, we have to look at all possible coupling paths for HEMP-energy.

Figure 13 shows possible locations for early time HEMP coupling, sometimes also referred to as short pulse HEMP or E1 coupling. This PV-system is an advanced system that uses battery storage for continuous power supply also during the night.

E2 or intermediate time HEMP coupling is not considered to be a threat for such a system, because E2 couples effectively only into cables longer than 100m. If such a system were connected to the power grid, then of course E2 could not be neglected. However, such protection filters are readily available on the market and are not considered here.

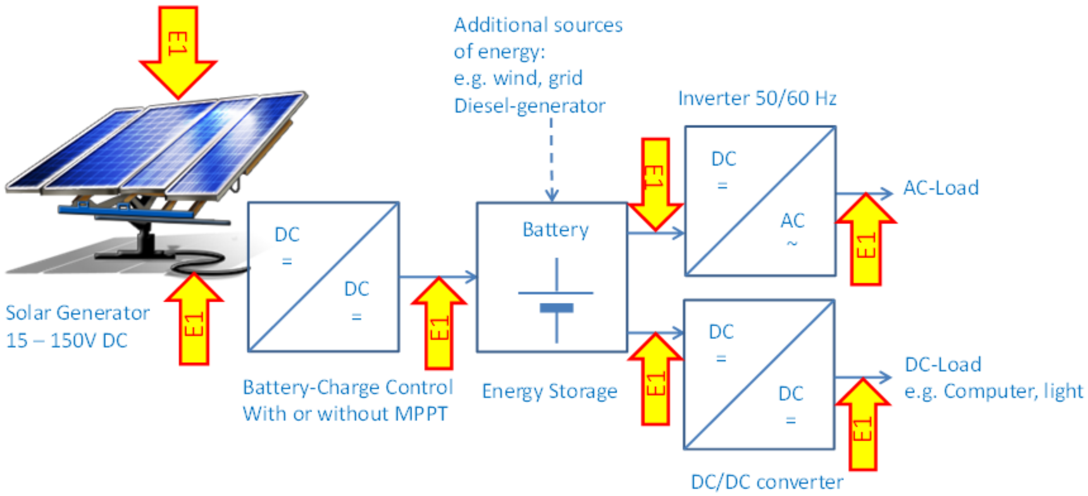


Figure 13: E1 coupling paths for HEMP and lower frequency coupling to PV-systems

5.2 Protection of PV-systems

The extensive tests have shown that shielding of PV-modules is definitively not required. However, two things are important: to protect the bypass-diodes in the modules from reverse surge currents, and to protect the subsequent electronics, such as inverter, battery storage and control electronics.

In **Figure 14**, typical protection measures and their locations are proposed. The PV-generator can be equipped with transient voltage suppressor (TVS) diodes, either for each PV-module, or at least for every string. This protects from fast surges in the cabling, especially from surge currents in reverse direction.

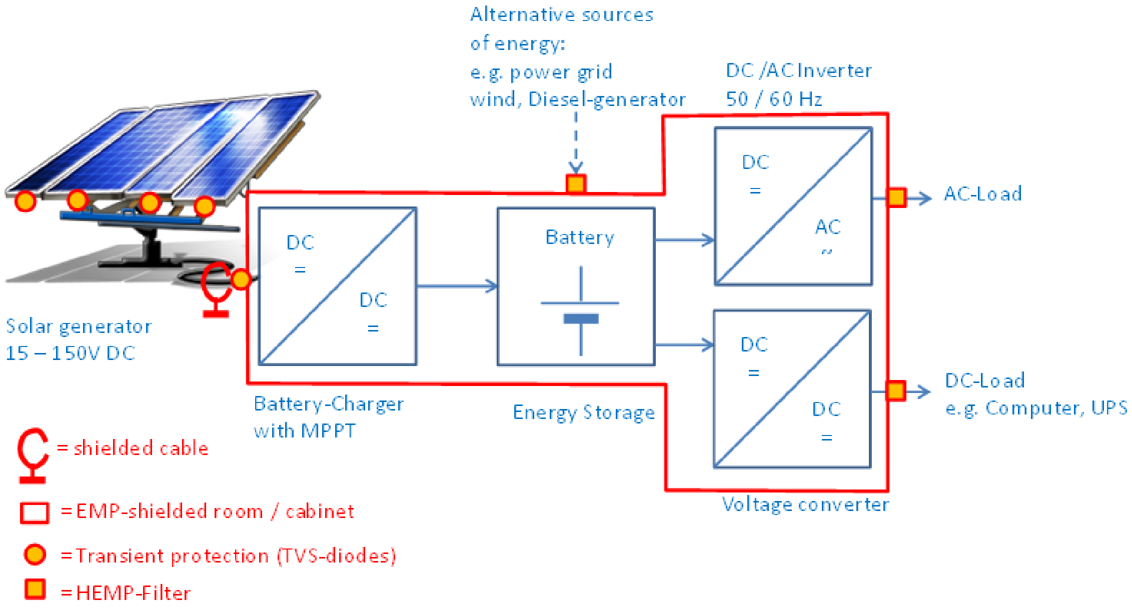


Figure 14: Transient voltage suppressors on modules and integral shielding enclosure of control system

Furthermore it is suggested to shield the cables from the PV-generator to the inverter. This not only prevents HEMP-coupling, but it also is a good protection measure against lightning currents. Furthermore it provides some mechanical rigidity to the cable, which is exposed to the weather.

Subsystems containing electronics, like inverter, battery charge control and others, can be easily protected by installing them in a metallic cabinet, providing some degree of shielding. The incoming unshielded wires, e.g. the connection to the power grid, have to be protected by conventional HEMP-filters, which should also be able to protect against lightning threats.

6 CONCLUSIONS

Electrical energy is an important and critical factor for critical infrastructure. Beside other protection requirements, HEMP-protection is often also required to protect critical infrastructure. In this context, the idea came up to use PV-generators not only as a source of renewable energy, but also as part of the emergency power supply. This raised the question, whether it is possible to protect PV-generators against HPEM-threats, especially HEMP.

The goal of this work was to assess the EMP-hardness of PV-generators, and to show if hardening against HPEM disturbances is possible. Extensive experiments on the component level, as well as on PV-modules of different technologies were carried out. It was shown that photovoltaic cells and modules are much more robust against HPEM-threats than commonly expected. Tests of modules in different orientations in an EMP-simulator have shown that shielding of the modules is not necessary. Even HEMP-fields of up to three times the threat-level did not damage the modules under various load conditions.

However, bypass-diodes are relatively sensitive to reverse surge currents. Therefore, it is concluded that some protection against conducted disturbances in the cabling is required to avoid surge currents in reverse direction of the diodes. By shielding the cables and by adding TVS diodes, the PV-generator can be hardened at reasonable cost. In addition, well-known protection measures can be used to protect the electronics, such as inverters, battery storage system and control system.

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