International Conference on Renewable Energies and Power Quality (ICREPQ'19)
Tenerife (Spain), 10th to 12th April, 2019
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.17 July 2019

PV power stations – fire hotbeds and fire tolls

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Abstract. This article deals with photovoltaic power stations acting as possible fire hotbeds and simultaneously fire tolls. Main PV features defining fire risks of alone standing or on building mounted power station are discussed. Analyses described in main chapter are based on real case of a lightning strike. Divergence between direct lightning strike and close lightning strike is deeply illustrated and possible protections are discussed. Following paragraphs deal with fire rating and fire performance of particular PV panels, relevant dangers for acting firemen, extinguishing ways, particular fire progress and secondary hazards. The problematic is demonstrated on the base of experimental photovoltaic plant fire and real examples of injured panels.

Key words

PV panel damage, PV power plant fire, lightning strike, secondary hazards of PV systems.

1. Introduction

Each component of photovoltaic power station is fully exposed to ambient conditions including several types of particular unpleasant effects. These situations can affect only operation and life cycle of the system itself, but some of them can lead up to malfunctions or injuries resulting in extreme case in the fire. Reciprocal accouplement with surrounding structures and objects can then lead to significant additional economical losses. By contrast the neighbouring objects can during innate fire affect the power station with the same results [1], [2].

2 main common design cases depending on PV power plant purpose have different effect. First case is a domestic or industrial power station installed either on the roof or on the walls of a building. Direct linking between the power plant components and the building structure is evident. Second case represents large stand alone PV power plant with no important surrounding objects [4].

The paper was supported by SGS-2018-023.

Events with natural background or specific human activities can, from our point of view, abstractedly on the motive lead in the consequence to the fire. PV power stations installed on buildings are more endangered then stand alone installations. The fire can be initiated inside the building independently of the plant components. Faulty electrical installations, defective house appliances or some misfortune events are good examples. On the other hand PV plant components can itself initiate the fire. Electrical component malfunctions or unpredictable result of natural events are typical events. Fig. 1 shows roof mounted PV power plant after fire of the building.

Fig. 1. Roof mounted PV power plant after fire.

One of the most destructive natural events is the lightning strike. The lightning strikes directly into the power plant or the discharge hits some surrounding constructions. PV panels are fully destructed. Strong lightning current melts metal panel frame and the semiconductor structures. The results can be compared to the direct fire exposition presented on Fig. 1.

Large stand alone PV power plants are paradoxically smaller problem from the fire point of view. These systems are usually installed on a free area. No surrounding objects are to be affected or to affect the plant as demonstrated on Fig. 2 [3].

Fig. 2. Stand alone PV power plant after fire.

The research is based on analysis of several practical cases and model situations, while almost no theoretical backgrounds are affordable [5].

These events are rather rare, but mechanical damages, wires broken during storm winds or bitted by animals can lead to the same results. Damage of the plant and building structures is visually evident and also affected panels can be easily identified [4], [5].

The other situation is much more frequent. Consequences are more difficult to identify, because the damage itself is caused only by some overvoltage. Although the semiconductor structures show serious malfunctions, the panel and surrounding objects are visually not affected or the particular degradation is almost not evident. Fig. 3 shows smoke traces on the backside of a panel damaged during lightning strike into close chestnut tree [3].

Fig. 3. PV panel damage after close lightning strike.

2. Analyses of the close lightning strike

Commercial photovoltaic power station "A" was damaged during a storm. Decreased power production during following days logged at output side of the power station indicated some malfunction of the system.

Quick service check detected extensive problems in string No. 1. No visible damage was evident but neither output string voltage, nor output string current reached the nominal values. These attributes indicated internal malfunction of one or more panels in the string. Particular analysis discovered one specific panel CanadianSolar CS6P-245P declaring malfunctions. Also serious damage of the string inverter was detected.

Power plant is installed on base metal structure anchored on flat roof of an industrial hall. Although the system is covered with protection angle of primary lightning protection system, auxiliary lightning rods were connected to the original conductors. Surge guards installed in central switch board represent secondary protection. No damage of protection system was identified.

Subsequently a lightning hit into chestnut tree standing 15 m far from the industrial hall was located. Few superior branches were broken off and the trunk showed burn traces from the lightning downlead. Because the trunk had not been split, the lightning was classified as rather small. Close distance between the tree and the industrial hall caused that overvoltage had been induced between the supporting structure and wiring of the photovoltaic power plant [3].

Existence of the storm was explicitly documented from meteorological reports and radar snapshots archived by Czech hydro meteorological institute (CHMU).

The panel analysis was performed in the Laboratory of renewable energy sources belonging to Faculty of electrical engineering at University of West Bohemia. Analyzer HT Solar I-V 400 was used. Electrical measurements in real conditions were supplemented with synchronous measurements of panel temperature and incidenting radiation. The radiation oscillated between 315 and 983 W/m^2 while the panel temperature alternated between 12.1 and 30.3 °C.

No usable VA-characteristic was recorded. Example measured in conditions very close to STC (I_p = 983 W/m^2, t_P = 26.8 °C) is demonstrated on Fig. 4.

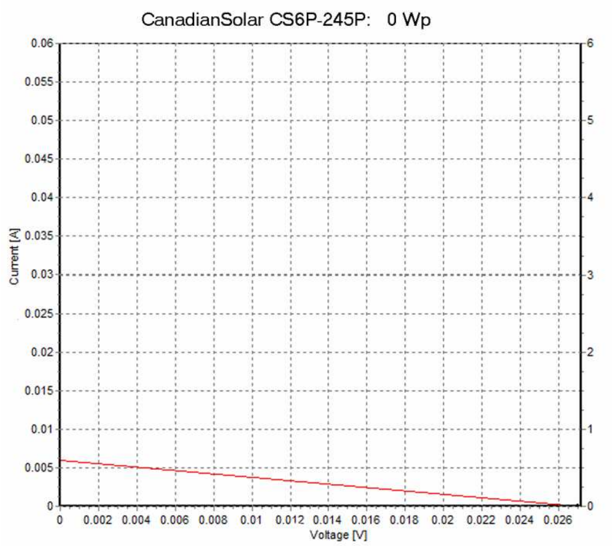

Fig. 4. VA-characteristic of tested panel.

The nominal output voltage of the tested panel at STC is U_{MAX} = 35.6 V and nominal current is I_{MAX} = 6.7 A. The output voltage dropped almost to 0 V while the output current almost did not ascended above 0 A once the load was connected to the panel during the measurements. The panel was disconnected and shaded to cool down before this measurement to get as close to STC as possible for the particular experiment.

As evident from Fig. 4 maximum power point (MPP) was also not measured. The only sign of partial functionality is some low value of open circuit voltage recorded during additional measurements and presented in Table 1.

TABLE I. OPEN CIRCUIT VOLTAGE OF TESTED PANEL

I_P [W/m^2]	92	157	204	261	309	360	448
t_P [°C]	18.5	19.1	19.4	19.9	20.3	21.6	25.7
U_0 [V]	10.28	10.29	10.31	10.33	10.37	10.39	10.44
I_P [W/m^2]	516	572	612	663	691	737	865
t_P [°C]	26.4	28.1	29.8	31.2	32.1	34.9	36.3
U_0 [V]	10.45	10.47	10.48	10.52	10.56	10.59	10.64

Built in bypass diodes were disassembled from the wiring box and measured separately. No diode malfunction was detected while all strings of the panel are affected by the lightning event. Despite of heavy panel damage, no fire was initiated.

3. Simulation of direct lightning strike

Experimental monocrystalline Si panel Solartec STR-36-13 was tested in high voltage laboratory of University of West Bohemia as target of high voltage discharge to simulate direct lightning strike. Metal frame of the panel was grounded (electrode 1) while the high voltage (electrode 2) was connected to the surface of the panel.

Firstly surge pulse generator EM Test VCS 500 was used to generate voltage pulses up to 10 kV. Panel VA characteristic and basic values were measured after each pulse to verify status of the panel. No panel breakdown was detected as evident from Table 2.

Nominal values of the panel (prior all experiments) are summarized in the first column (U_p = 0 kV).

TABLE II. PANEL CONDITIONS AFTER HV PULSE (10 KV)

U_P [kV]	0	2	4	6	8	9	10
U_{0C} [V]	21,56	21,55	21,56	21,57	21,54	21,55	21,57
I_{SC} [A]	0,82	0,82	0,83	0,83	0,81	0,82	0,81
U_{MPP} [V]	17,42	17,41	17,41	17,41	17,44	17,43	17,43
I_{MPP} [A]	0,74	0,75	0,74	0,73	0,75	0,75	0,73
P_{MPP} [W]	12,89	13,05	12,88	12,71	13,08	13,07	12,73

Sample waveform printscreen of generated HV pulses for U_p = 2 kV is demonstrated on Fig. 5.

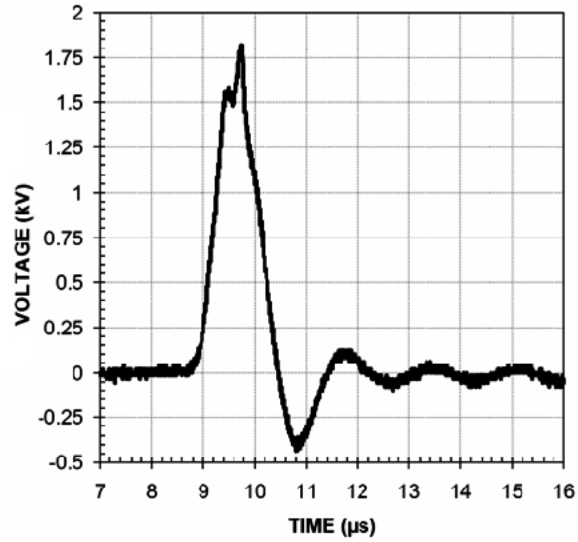

Fig. 5. Sample pulse 2 kV (EM Test VCS 500).

Because no evident influence was detected, the panel was connected to 8 stage HV generator Heafely capable to simulate atmospherical pulses 1,2/50 µs up to 600 kV. Table 3 illustrates panel status after particular tests.

TABLE III. PANEL CONDITIONS AFTER HV PULSE (600 KV)

U_P [kV]	50	100	200	300	400	500	600
U_{0C} [V]	21,53	21,54	21,58	21,52	21,56	21,57	21,53
I_{SC} [A]	0,81	0,83	0,83	0,84	0,86	0,85	0,86
U_{MPP} [V]	17,44	17,45	17,43	17,42	17,46	17,42	17,44
I_{MPP} [A]	0,76	0,74	0,73	0,74	0,74	0,76	0,75
P_{MPP} [W]	13,25	12,91	12,72	12,89	12,92	13,23	13,08

Table 2 and Table 3 show that no measurable panel damage was detected on VA characteristics. That could be explained with insufficient energy of generated pulses although the discharges produced very dramatic visual effects as demonstrated on Fig. 6.

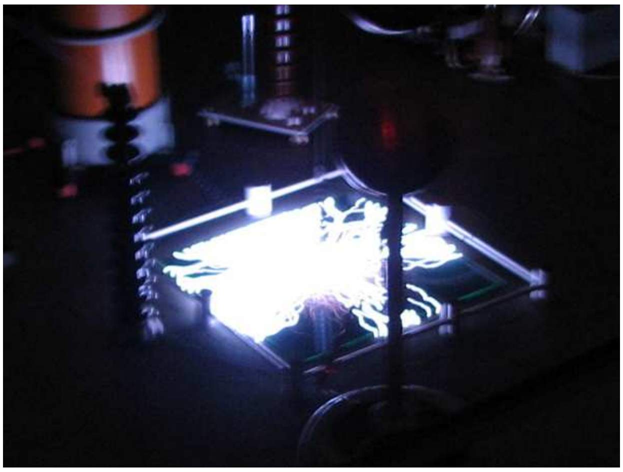
Fig. 6. Sample pulse 600 kV (Heafely generator).

Sample VA and power characteristic after all measurements is displayed on Fig. 7. No deformation similar to Fig. 4 is evident and the values are proper to nominal listed in Table 2. Also no visual damage similar to Fig. 2 was detected.

Demonstration discharges did not simulate direct lightning strike with proper results.

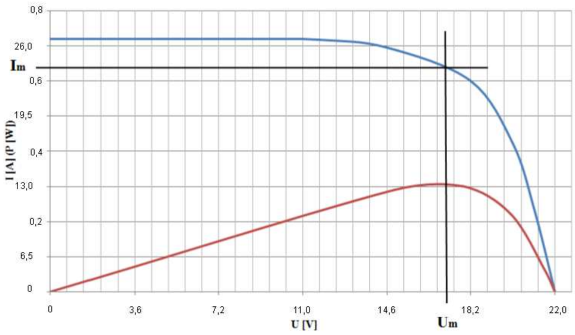

Fig. 7. VA characteristic after all tests.

4. Experimental fire of model PV power plant

To analyze all real conditions and features experimental fire of model power plant was prepared. Main goals of this particular experiment were defined:

- dangers for the firemen
- fire rating and fire performance
- ways of extinguishing
- secondary hazards
- progress of fire

Experimental PV plant was built on the roof of an old military building determined to be demolished. Configuration of the experimental plant on the building roof is displayed on Fig. 8.

Fig. 8. Experimental PV plant configuration.

Special additional measure lines were designed and thermally shielded in wooden canals to acquire relevant data during the fire. Panel temperatures, output voltage and current, VA characteristic and thermographs were measured periodically.

The power station consisted from 4 strings wired from 12 monocrystalline Si panels Solartec ST-36-53. Particular separate strings were installed on different roofing materials:

- roof tiles
- metal plates
- tar paper

Ambient conditions were defined by cloudy weather with solar radiation varying between 150 – 250 W/m^2 and air temperatures from 8 °C to 11 °C. Although these conditions are far from STC and are less positive for power generation from PV plants, define practical limits for PV plant operation and thus margins for fire of operating PV power station.

Dangers for the fire fighters entering the object with PV power plant and secondary hazards during and after the fire were identified and discussed with fire department during the preparation phase:

- touch voltage (AC, DC)
- step voltage (AC, DC)
- DC currents (water electrolysis – H_2 production)
- DC shortcuts (fire reinitiation)
- DC sparks (fire reinitiation)

Fig. 9 presents sample measurement of secondary hazards – DC sparks. One of the output wires from PV string was grounded while the second one was freely and randomly used to ignite sparks on surrounding objects.

This situation often happens, when power wires are broken (burned or cut) and loosely hanging in the space. Any contact between the wires among each other can ignite a spark. Also random touch of one wire with some metal object (water drips, pipes, girders, sheetmetals, etc.) while the second wire is in synchronous contact with that object can initiate shortcut current and/or sparks.

Fig. 9. Sample of secondary hazards – DC sparks.

Although the ambient conditions were not ideal, experiments proved that these sparks have enough energy to initiate a fire of several typical flammable materials as shown on Fig. 10.

Fig. 10. Energy of sample DC sparks.

Surprisingly usage of low pressure or high pressure water beam (with complementary insulation devices) was found as the best way of extinguishing. Extinguishing foam and powder demonstrated weak and unstable effects.

DC currents represent also another type of hazard that must be on mind while using water beam for extinguishing. Water electrolysis occurs in wet ambient, what means H_2 and O_2 production. Any higher H_2 concentration brings high explosion risk especially in environment with common initiating electric sparks. Fig. 11 demonstrates generation and caption of H_2 in some enclosed space (plastic bottle).

Fig. 10. H_2 generation in enclosed space.

The fire was artificially initiated in the right front corner of the attic under fire department supervision. Firstly the string on the tar paper roof was affected, then both strings on metal roof and finally the string on tiled roof. The roof collapsed in time 10:35 min and panels were almost destroyed as evident on Fig. 1. The fire was kept down after 14:00 min while the typical fire progress is:

- 0. min: fire initiation
- 2. min: fire detection
- 3. min: call to fire department
- 5. min: departure of fire units (distance 10 km)
- 15. min: start of fire attack

Measured VA and power characteristics of string 1 during the fire are presented on Fig. 11, Fig. 12 and Fig. 13. The partial power decrease on Fig. 12 can be explained with smoke shading the panels, while Fig. 13 shows zero output of damaged string.

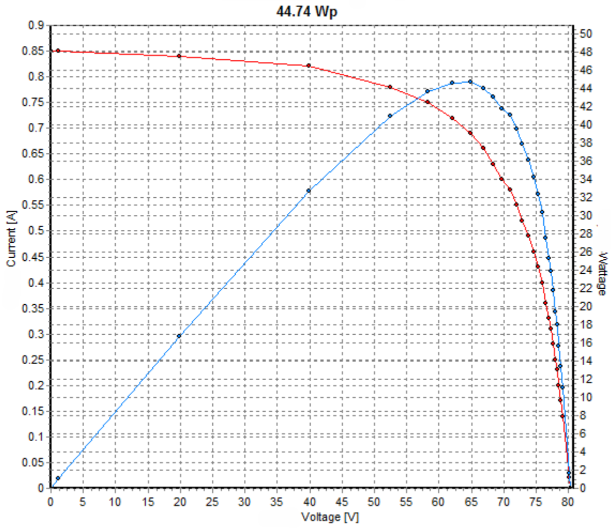

Fig. 11. Sample VA characteristic (time 0:00 min)

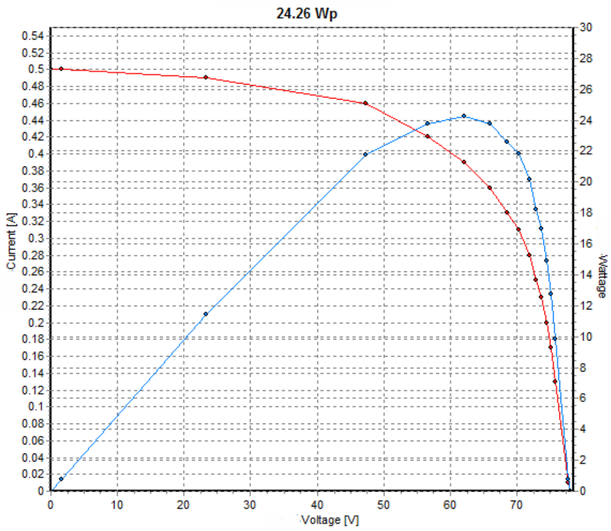

Fig. 12. Sample VA characteristic (time 6:35 min)

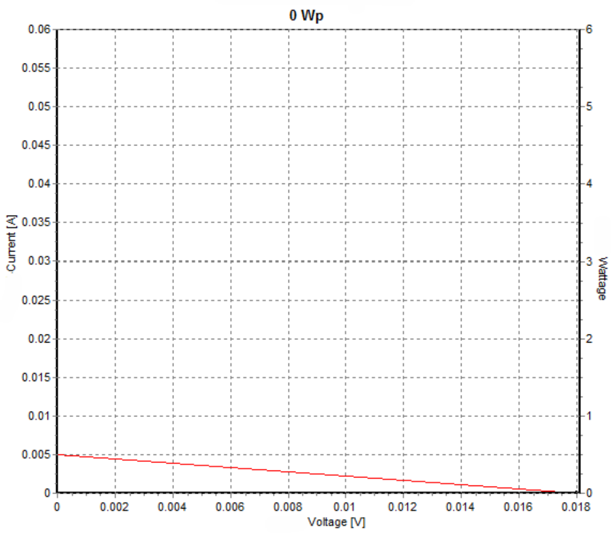

Fig. 13. Sample VA characteristic (time 10:12 min)

Sample thermogram from the fire progress (4:45 min) is demonstrated on Fig. 14. Panels on metal roof (middle of the picture) and panels on tiles (left part of the picture) are not affected yet, while panels on the tar roof are in the flames (upper right part of the picture).

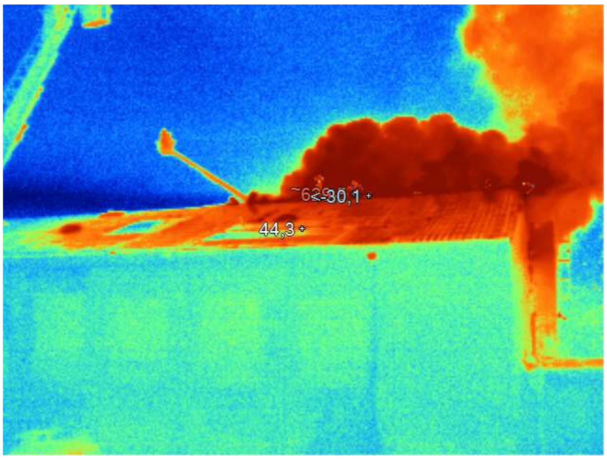

Fig. 14. Sample thermogram (time 4:45 min).

Fig. 15 shows the output voltage of all strings. It is evident that voltage fluctuated and even exceeded the nominal value. This unpredicted behaviour has simple explanation. Burned wires composed random temporary connections leading to overvoltage and even reverse voltage on the string output.

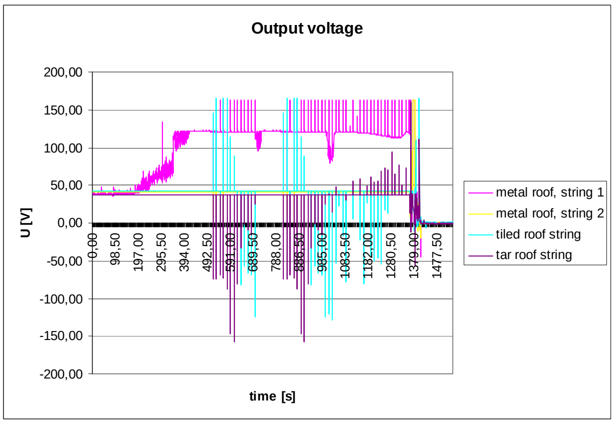

Fig. 15. Output voltage during the fire.

5. Conclusion

Described experiments and measurements demonstrate particular effects of specific types of natural events and human activities on photovoltaic power plant operation.

Analysis and simulations of close and direct lightning strike show dissimilar influence on the innate PV plant and surrounding constructions. Close lightning strike can induce harmful voltage to power cables or to surrounding structures that is capable to injure the panels without additional consequences, while direct lightning strike is powerful enough to completely damage the devices and also to initiate a fire.

Direct fire incidence on photovoltaic plant always means serious results. Beyond typical effects such as touch and step voltage, DC currents characteristic means specific hazards as H_2O electrolysis and DC sparks. It is also evident that actual voltage value can not be predicted in any way and can reach dangerous values, although the nominal value is safe.

The paper was supported by SGS-2018-023.

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