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Evaluation of long term degradation process of monocrystalline Si photovoltaic panels

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Abstract. The paper focuses on evaluation of long time degradation process of the oldest grid-on operated photovoltaic system in Czech Republic.

Monocrystalline silicon cells yield to specific degradation through their life cycles. The degradation can be stratified into material degradation of the essential silicon wafer, material and mechanical degradation of other compounds of the panel and degradation of electrical substructures and components.

The degradation process is affected with particular fabrification procedures and with some operating conditions. While the fabrification is out of control of the end user, the operating conditions can be partially influenced by the user. Although the weather and ambient values are the strongest acting factors, also the operating regime can significantly affect the life cycle of the panels.

A photovoltaic power plant consisting from 192 monocrystalline silicon panels with installed power 20 kWp has been operated for more than 15 years. The system has own monitoring system logging particular electrical and non electrical values in 10 min interval. This data are used for basic monitoring of the system. The system is deeply inspected annually with thermovision and VA characteristic check of each panel.

The main contribution of this article is evaluation of the data from 15 years of operation. Dramatic change of state was identified between 2018 and 2019. Significant amount of panels shows already visible traces of degradation such as microcracks, hotspots and connection faults.

Key words. degradation of photovoltaic panel, monocrystalline Si panel, microcrack, hotspot, PV panel life cycle.

1. Introduction

Photovoltaic power plants of all sizes became conventional part of power sources mix since 2004. Although photovoltaic systems contain no mechanical components they are very sensitive to operating conditions and regime. The most significant factor is the installation in open area and thus direct exposition to harmful ambient conditions. These conditions can lead into wide set of operational failures or malfunctions and affect the degradation process of particular components [1, 2].

Faculty of electrical engineering in Pilsen was one of the first photovoltaic operators in Czech republic connected to the grid. 20 kWp photovoltaic power plant was built during construction of new faculty building in Bory campus. The plant was supported by 5th European Union Framework "PV Enlargement" and became the largest commercial grid on system in central Europe until 2005 when it was overpowered with 40 kWp system installed on University of South Bohemia [4].

The system is installed on flat roof, situated southbound, inclined in 45° angle and consists of 192 monocrystalline Si panels Isofoton I-150 covering area 165 m^2. Panels are connected into 8 strings with one phase inverters Sun Profi SP-2500 installed in a special room below the roof. The inclination 45° was standard solution at that time as a compromise for full year operability with maximal efficiency. The panels are designed from dark blue cells, what later became a standard colour for new installations for its best efficient. More important for the colour during this installation were architectonic and aesthetic reasons. Generated energy is supplied into the public grid via main switchboard inside the inverter room. The general view of the system installed on the building of Faculty of electrical engineering is on Fig. 1. [5]

Fig. 1. General view of the experimental 20 kWp PV plant

The PV system is equipped with measuring chain continuously logging:

- main meteorological conditions
- global solar irradiance
- temperature of the array
- DC, AC voltage and current
- output power (P, Q, S)
- power factor
- phase unbalance
- total harm. deformation (U, I).

2. Degradation of the system

The 15 years of operation is one of the longest period of commercial photovoltaic system operation. The system was periodically tested with thermocamera Flir Tk 355 and VA characteristic analyser HT Solar IV-400.

While measurements performed between 2004 and 2018 did not show any significant anomalies, initial visual check of the PV array detected strong progress of the degradation.

Table I briefly shows annual progress of the plant degradation and annual electricity production. The inverter malfunctions indicate only broken fuses and not serious problems. 2 panels are defective since 2013 and both have one defective cell. Malfunctions in category “Other” mean usually problems with measurement system except one problem with lightning protection in 2004.

Table I. – Annual malfunctions of the plant

	Panels	Inverters	Cables	Construct	Other	Energy [%]
2004	0	0	0	0	5	100
2005	0	0	0	0	0	101
2006	0	0	0	0	0	101
2007	0	0	0	0	1	102
2008	0	1	0	0	0	103
2009	0	0	0	0	0	101
2010	0	0	0	0	0	103
2011	0	0	0	0	0	102
2012	0	1	0	0	0	101
2013	2	0	0	0	1	104
2014	2	0	0	1	0	100
2015	2	0	0	0	0	99
2016	2	0	0	0	2	99
2017	2	0	0	0	1	100
2018	2	0	0	0	1	99

Table II presents in detail malfunctions detected in summer 2019 on the photovoltaic array. The numbers mean amount of affected panels not amount of particular defects. Affected panels (above all in case of cell degradation) have more defects in most cases, so the total number of defective panels is 116.

Table II. – Detected Panel and String Malfunctions

Malfunction	**Suma**		**Behaviour**
	-	%	
aerial pollution	128	39,7	dust layer and traces
cell degradation	117	27,2	colour changes
hotpot	37	8,5	local overheating
microcrack	36	8,4	crack
metalisation defect	34	8,1	broken conductors
bus defect	19	4,4	soldering corrosion
snail traces	18	4,1	material degradation
low transparency	15	3,7	glass / EVA degradation
yellowing	9	2,1	EVA degradation
local pollution	8	1,9	birds excrements
bad connector box	5	1,2	corrosion, PVC degrade.
bad connection	3	0,9	overheating, corrosion
water in panel	1	0,4	delamination
broken glass, EVA	1	0,4	mechanical impact
Total	**431**	**100**	

3. Annual measurements of the system

All 192 panels are analysed annually since 2004. Thermocamera Flir Tk 355 is used for initial check of the array. Panels with strange behaviour are checked deeply. 2 defective panels were detected 2013. No progress of the degradation was identified during successive tests until 2018.

Sample thermogram of the first deffective panel (no. 84) from 2013 is demonstrated on Fig. 2. Deffective cells in string 4 are evident. Thermograms from 2014 – 2018 are identical.

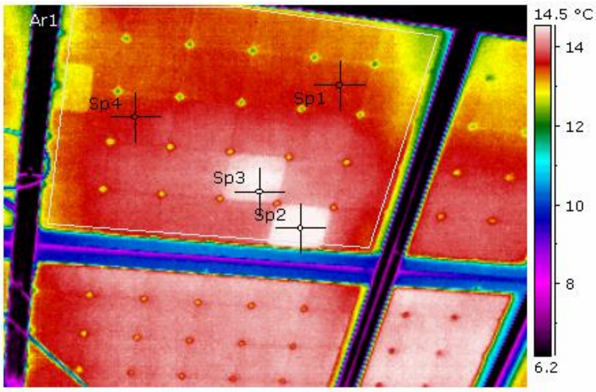

Fig. 2. Sample thermogram of panel 84 (2013)

All panels were disconnected from particular strings and individually measured with VA characteristic analyser HT Solar IV-400. Sample VA and power characteristics of healthy panel are shown on Fig. 3 (panel 1, 2013). Example from 2013 is selected, because these measurements has detected first malfunctions.

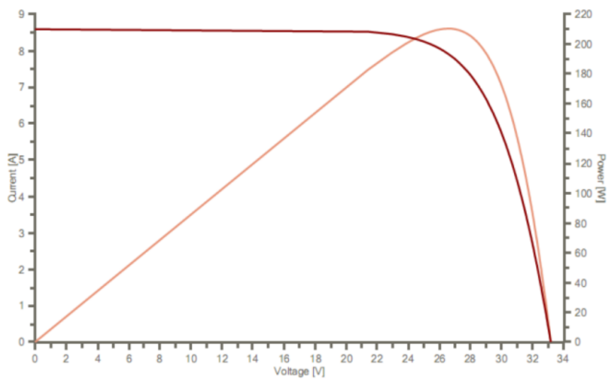

Fig. 3. Sample characteristic of panel 1 (2013)

Comparison of VA characteristics between healthy and defective panels is demonstrated on Fig. 4. Particular data are summarized in Table III. Measurement 24 shows healthy panel (panel 1), while measurements 25 and 26 show defective panels (panel 84 and 141).

Table III. – Measurement Details (panel 83, 84 and 141)

Measurement	P_m [W]	U_{oc} [V]	U_m [V]	I_m [A]	I_{sc} [A]	I [$W.m^{-2}$]	T[℃]	Fill Factor [%]
24	142,98	38,96	29,44	4,86	5,34	731,00	17,40	69,00
25	132,97	39,10	32,44	4,10	5,61	786,00	19,00	61,00
26	94,86	39,01	19,15	4,95	5,42	745,00	19,40	45,00

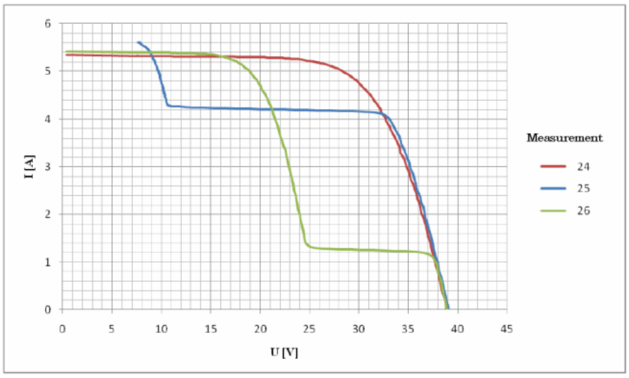

Fig. 4. Sample VA characteristics of panels 83, 84 and 141

4. Degradation detected during 2019 check

Massive degradation of particular panels was detected before annual measurement 2019/2020. All cases are summarised in Table II.

Sample of strong delamination (white areas) and massive cell degradation (dark cells) is demonstrated on Fig. 5. Both defects (panel 34) are evident in the middle of the picture. 116 panels showed cell degradation in similar size or different type of defect from Table II.

Fig. 5. Sample of delamination and cell degradation (panel 34)

Material degradation of particular cells in most cases of 117 affected panels is detected not on a single defective cell but on certain amount of defective cells. Affected cells usually create some pattern as shown on Fig. 6. This dependency indicates some technological problems during the fabrification process. The most presumable reason is the homogenity of the raw silicon material or the homogenity of the gaseous environment during the passivation process [1].

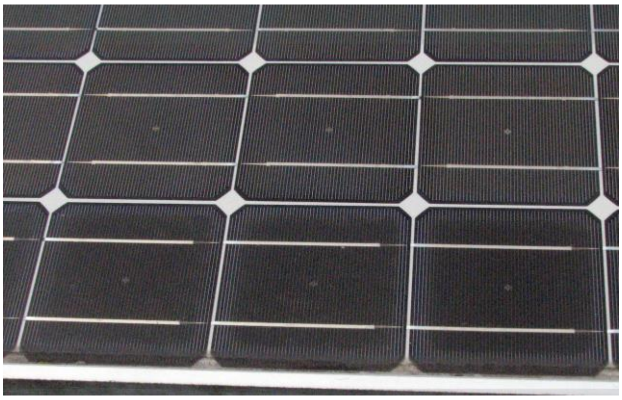

Fig. 6. Sample of the hotspot (panel 51)

Typical hotspot was detected on 37 particular panels. Sample of this phenomenon (panel 67) is presented on Fig. 7.

Typical behaviour is overheated area with broken conductors or collectors on the frontal side. Also thermal degradation of EVA on front and back side occurs, if the malfunction lasts longer time [3, 4].

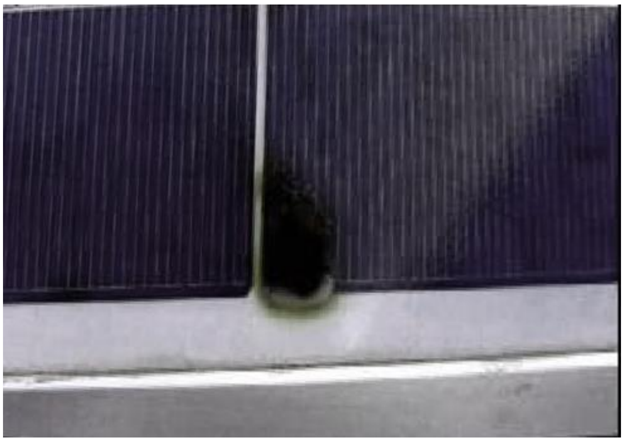

Fig. 7. Sample of the hotspot (panel 67)

Very unpleasant situation is a rupture of the backside EVA or the frontal glazing. The panel is opened for humidity, what results in fatal malfunction of the panel. Sample of degraded backside EVA is presented on Fig. 8. (panel 81).

Fig. 8. Sample of degraded backside EVA (panel 81)

36 new particular microcracks were identified during the 2019/2020 analysis. Two typical examples of the microcrack are presented on Fig. 9 (panel 104). This panel is unique, because it is the only panel with more than 1 cell with a microcrack. The right cell is an example of star shaped microcrack while the left one is a sample of linear microcrack.

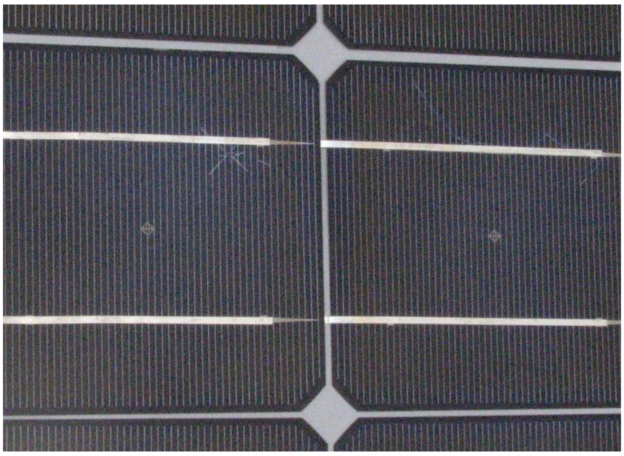

Fig. 9. Sample of microcrack (panel 104)

The microcrack is the result of the local non-homogenity and thermal stress. Typical behaviour of this malfunction is a gradually expanding crack that slowly parts the cell in one or more direction. The edges initiate other thermal stress and degradation of the whole structure [1, 3, 6].

Another problem with the homogenity of the fabrification process or the raw material can be observed as so called snail traces. These symptoms can be found on the front side of affected cell as demonstrated on Fig. 10. Panel 88 is good example of 18 detected malfunctions.

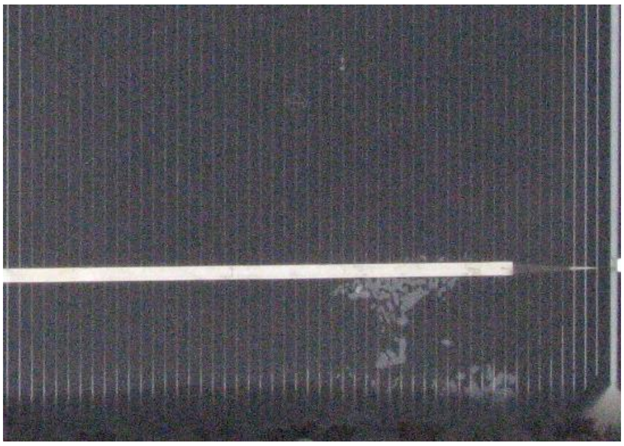

Fig. 10. Sample of snail traces (panel 88)

Almost all of 192 panels show significant traces of massive aerial pollution accompanied with the degradation of covering material. These traces can be found on the bottom edge of the panels. Metal frame in this part of the panel restrains attached pollutants to be completely washed out from the surface during natural rains, the pollutants start to create a layer that slowly becomes solid and sturdy.

Not only physical stress but also chemical processes degrade the surface. The environment becomes slowly pleasant for micro-organisms and biological corrosion is started.

Typical example of this phenomenon on panel 21 is illustrated on Fig. 11 (upper panel). The pollution creates a stripe approximately 1 cm high. Also the corrosion of the aluminium frame are evident on the upper panel.

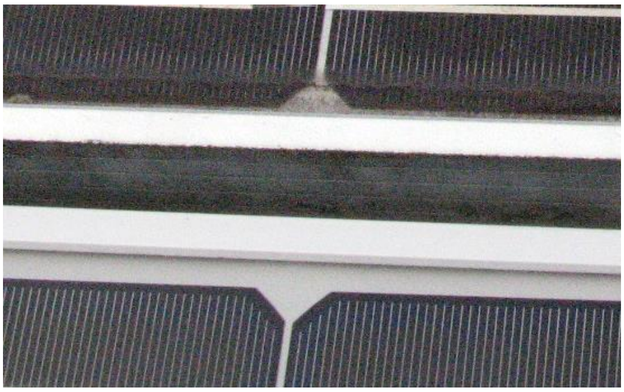

Fig. 11. Example of aerial pollution and corrosion (panel 21)

5. Degradation analysis

Samples presented in previous chapter demonstrate the degradation that was detected during the last system check. What is interesting, is not the degradation itself, but the process of the degradation. While during 2018 check only 2 defective panels were identified, 2019 measurements show significant evolution of 116 panels.

Not every detected malfunction has the same influence on the panel behaviour. Although the effect at present time is not significant, it could lead into very serious problem in close or more far future.

Example of this malfunction type is demonstrated on Fig. 12. Reference VA characteristic of healthy panel shows measurement 22, while number 23 presents the panel 88 affected with the snail trace. This defect covers approximately 2 % of the area on 6th cell in the 1st string.

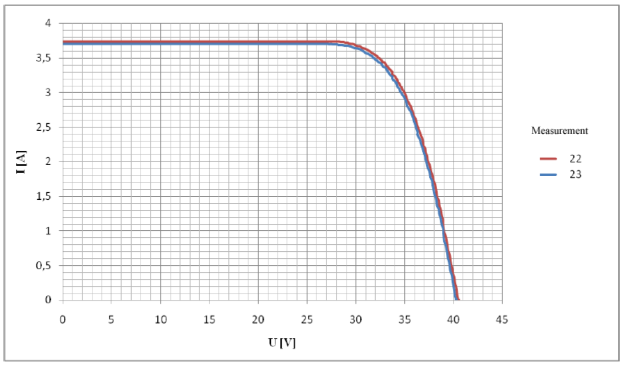

Fig. 12. Sample VA characteristics of panels 87 and 88

All less serious malfunctions (snail traces, local pollution etc.) have similar influence on the VA characteristic. It makes 177 cases from 431 detected issues.

Aerial pollution detected on 128 panels has no measurable influence on the panel behaviour at present time (or the influence could not be identified because another malfunction is present at the panel).

All other malfunctions (hotspot, microcrack, metalisation defect etc.) have more significant impact on the VA characteristic. This set personate 126 cases (29,2 %). Fig. 13 shows samples of this behaviour. Reference VA characteristic of healthy panel shows measurement 7. Cases 8 and 9 demonstrate influence of the hotspot on one sole cell, while measurements 10 and 11 illustrate the same malfunction but on 2 cells connected into independent strings. Examples 12 and 13 show particular microcracks of the star shape while number 14 presents linear microcrack. Curves 15 and 16 demonstrate defective bus connections in particular strings.

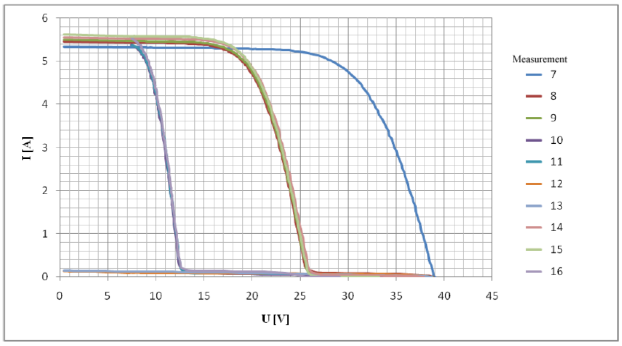

Fig. 13. Sample VA characteristics (measurements 7 – 16)

Direct impact of presented malfunctions on generated energy is demonstrated on Fig. 14 where power characteristics of affected panels are compared. Serious change of generated power and MPP position is evident.

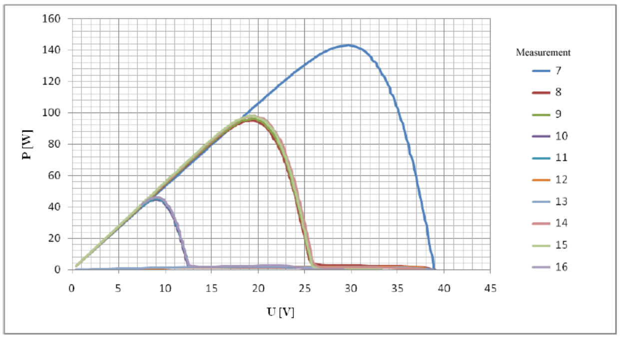

Fig. 14. Sample power characteristics (measurements 7 – 16)

6. Conclusion

Annual measurements performed on the oldest grid-on photovoltaic system operated in CR show interesting evolution of degradation process. Although this process is often simulated, this paper presents real results.

While measurements between 2004 and 2012 did not prove any significant changes, tests in 2013 identified first issues (2 defective panels). These conditions sustained constant until 2018. In general, only 2 panels from 192 showed some malfunctions during 14 years of continual operation. Not until 2019 any other malfunction was detected. At whole 431 particular malfunctions affecting 116 panels were detected during 2019 measurements. This represents 60,4 % of installed panels.

Interesting fact is not the large number of affected panels but the rapid change between measurements 2018 and 2019, which initiated this study.

2 particular scenarios of the degradation are possible. The first one predicts 2019 as the starting point of final degradation. The degradation will grow with constant speed. Another scenario expects staircase degradation. It means that the state detected in 2019 will stay almost constant for some period after which another strong degradation will be identified. Measurements in next years will prove, which scenario is correct.

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