PV Panel and PV Inverter Damages Caused by Combination of Edge Delamination, Water Penetration, and High String Voltage in Moderate Climate

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***Abstract*—There exist over 2 GW of photovoltaic (PV) systems in the Czech Republic, exposed to moderate continental climate. Although there exist many PV modules defects, thanks to the generally the same production year 2009, only some of them are usual at systems installed in Czech Republic. This work shows delamination failures that are frequent in moderate climate conditions. Special account is taken into edge delamination defect and its possible propagation in modules of standard construction. Combined PV panel and PV inverter failure is caused by edge delamination with water penetration and high string voltage. The electric discharge channel is created between the string of solar panels and the grounded PV panel frames. The result of the discharge channel created because of edge delamination is inverter switch-OFF and few months later total destruction of the inverter because of protective relay damage. The number of combined PV panel and PV inverter failures is increasing substantially after ninth year of operation of PV panels in moderate climate. Additional sealing of the PV panel frames by transparent polysiloxane gel reduced the number of combined PV panel and PV inverter failures very substantially.**

***Index Terms*—Delamination, photovoltaic (PV) modules and inverters damage, polysiloxane encapsulant, water penetration.**

I. Introduction

THERE is approximately 2 GWp of photovoltaic (PV) installed capacity in the Czech Republic. Such a large amount of standard design Glass/EVA/TPT aluminum framed c-Si modules represents a relatively good sample for evaluation of delamination defects at moderate climate. The average annual temperature in the Czech Republic is about +8 °C and average annual precipitation is about 700 mm. A very interesting fact in this case is the date of production is in almost all the cases in the year 2009. Since this time period, a few technological changes have been made but some of the problems still remain unsolved.

There are many defects that can appear during the PV modules lifetime. Some of them have origin in the manufacturing process and others can be caused by either wrong maintenance or even installation. The key parameter for defects evaluation is the performance, which is also the most important parameter for systems operators (performance represents money in the end).

Typical c-Si PV modules manufactured in the year 2009 used the Glass/EVA/TPT laminate design. The linear degradation rate of such panels is typically in the range of 0.7%–2.0% annually [1]–[3]. PV modules manufacturers usually declare the performance decrease to not exceed 0.8% for one year. Some of them guarantee this decrease to be linear, the other ones have the performance limits typically after 10 (12) and 25 years of operation (rarely after 30 years). This warranty counts with the performance decrease caused by the common operation, which also includes some types of defects like microcracks inside the cells that cannot be avoided. Contrarily, there are some other defects that can cause a significant decrease in performance and should be recognized and diagnosed in time to avoid larger losses of system as well as money.

In the following paragraphs, namely the delamination defects in combination with water penetration of modules installed in the Czech Republic are presented.

II. Delamination

The delamination process is usually connected with the manufacturing defects, or rather with the technological indiscipline. Delamination itself, when in low level occurs, does not represent serious endangering of the future reliability of the system, but if it occurs between the PV cells and the edge of the module, the substantial problems with isolation state of the module will arise.

From the point of view of delamination localization, it can be divided into the following four groups:

1) between backsheet foil and encapsulant;
2) between back encapsulant and the cell;

Manuscript received October 17, 2020; revised November 24, 2020; accepted January 8, 2021. Date of publication January 28, 2021; date of current version February 19, 2021. *(Corresponding author: Vladislav Poulek.)*

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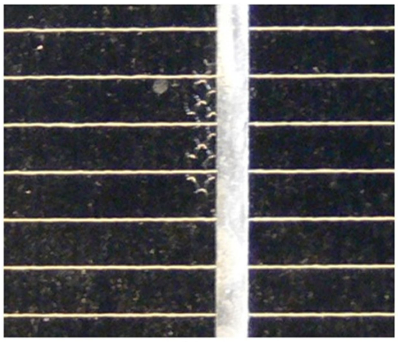
Color versions of one or more figures in this article are available at https://doi.org/10.1109/JPHOTOV.2021.3050984.

Digital Object Identifier 10.1109/JPHOTOV.2021.3050984



(a)

(b)

Fig. 1. Delamination between the front cover glass and encapsulant. (a) Early state. (b) Massive delamination.

Fig. 2. Edge delamination.

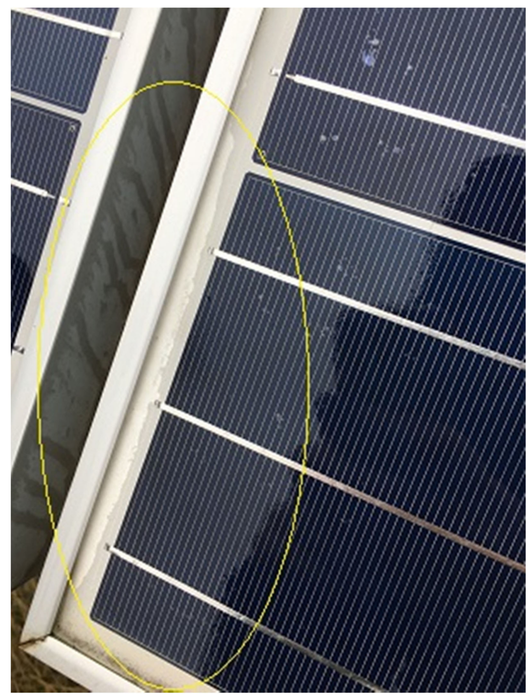


Fig. 3. Edge delamination.

3) between the cell and front encapsulant;
4) between the front encapsulant and cover glass.

The first and second types of delamination cannot be practically distinguished without module destruction, but the cause is usually the evolution of the gases inside the module that have no place to escape and then create typical bubbles visible on the back of the module. In the case of the first type of delamination, bubbles can also occur because of capillary forces at the EVA interface and backsheet foil. In this case, the bubbles reach larger dimensions and are filled with water under considerable pressure. When penetrating this bubble, the water spray is observable.

In the case of the third and fourth type of delamination, this phenomenon is easily observable through the front cover glass of the module.

In the case of the third type of delamination, destruction occurs almost immediately after the water penetration into the delaminated space because of the electrolysis application on the structure of the cell and the module busbars. This defect is, as well as type 2, accompanied by an immediate reduction of the insulation resistance between the frame and the internal structure (cells) of the module.

For the fourth type of delamination (see Fig. 1), bubbles behind the cover glass are observable, in the case of textured glass then the "glass opacity" occurs. In the case of subsequent moisture penetration into the system, the gradual water ingress toward the cells comes because of the hygroscopic properties of EVA and consequently also the gradual decrease of the insulation resistance occurs, resulting in degradation of the structure because of electrolysis.

From the point of view of International Standard EN 61215, delamination has two levels. The first level is its occurrence in small scale, where no future progress is usually presumed (typically around busbars). The second level is when the continuous path between the edge of the module and any cell inside is created. This leads to lowering of I_{SC} [4].

In the fourth type delamination slot, which typically occurs at the edge of PV laminate (see Figs. 2 and 3), water is regularly penetrating. The pure water is not very conductive, but namely at glass/EVA PV laminates the acetic acid is always present [5]. The mixture of water and acetic acid is more conductive. The critical delamination discharge channel is created when water is penetrating in delamination area between the PV panel string and the grounded PV panel frame. The result of the critical delamination failure is inverter switch-OFF and later total destruction of the inverter because of protective relay damage. The breakthrough between the grounded PV panel frame and the internal solar cell bus-bar with system voltage up to 500–800 VDC is usual. The

TABLE I
ANNUAL NUMBER OF PV PANEL CRITICAL DELAMINATION FAILURES AT DIFFERENT PV POWER PLANTS INSTALLED IN THE YEAR 2009 IN THE CZECH REPUBLIC

Location	Power (MWp)	No of panels	No of panels in string	String Voltage (V)	Inverter power (kW)	No of invert ers	Panel type	Number of destroyed PV inverter failures in the year			Number of PV panel failures in the year		
								2017	2018	2019	2017	2018	2019
Tuřany	5	18522	14	512	33	147	FT260	0	7	21(14%)	0	12	477
Měnín	3.3	18837	13	572	7	483	ST175	12	11	20 (4%)	0	3	292
Broumov	0.4	2160	18	666	45	8	ST185	0	1	4 (50%)	0	1	13

Fig. 4. Discharge channel between string bus bar and frame.

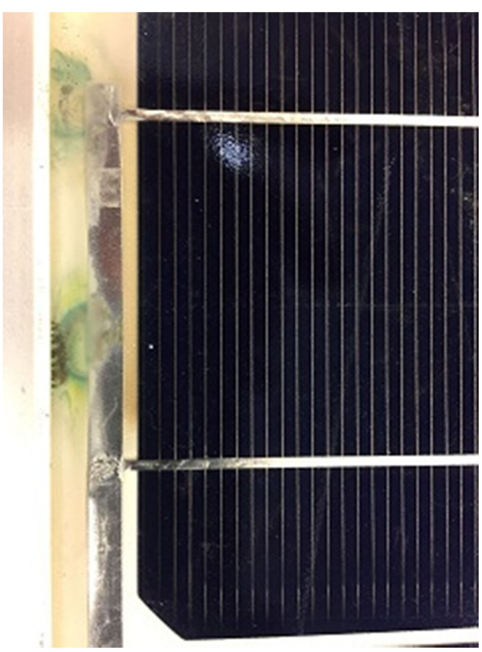


Fig. 5. Detail of another discharge channel.

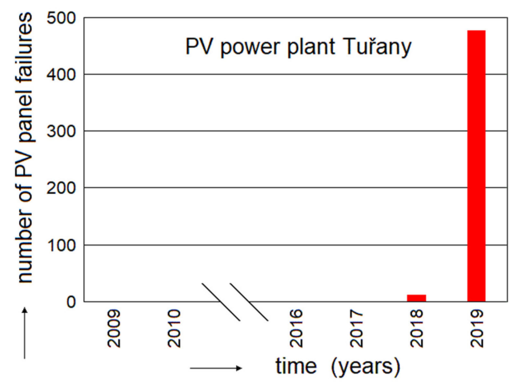


Fig. 6. Annual number of PV panel failures at Turany location.

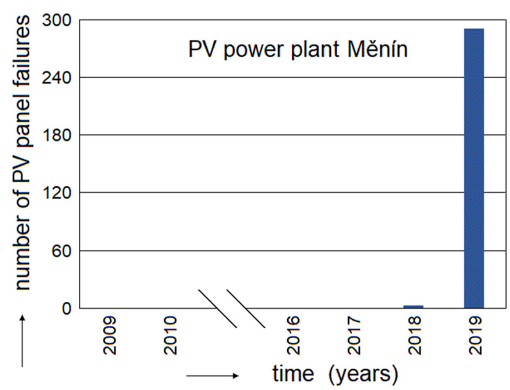


Fig. 7. Annual number of PV panel failures at Menin location.

typical discharge channel is clearly visible (see Figs. 4 and 5). In this case, the PV panels are irreversibly damaged (destroyed). The destroyed PV panel is not producing any power and it causes inverter switch-OFF because of low Risol.

The delamination at the edge of PV panels was observed on all 15 PV power plants older than ten years we are monitoring. A group of three PV power plants in the 0.4–5 MW range was investigated where we have complete set of data about all PV panels and inverters (see Table I). Till ninth year after installation, no breakthroughs were detected. The electric breakthroughs were detected at 0.3% of PV panels ten years after installation. After 11 years, 1% of PV panels were destroyed by breakthrough (see Figs. 6 –8).

Unfortunately, the single panel electric breakthrough is usually, within few months, destroying the inverter that is more expensive than the PV panel itself. The inverter usually has protection circuit monitoring the isolation resistance Risol but at frequent discharges between the PV string and the grounded PV panel frame, the protection circuit is destroyed as well as the complete inverter (see Figs. 9 and 10).

As the single damaged panel can either switch OFF or damage the multistring inverter servicing 10s of PV panels, such failure has a multiplication effect. Although the ratio of damaged PV

TABLE II
NUMBER OF LATE SWITCH-ON INVERTERS BEFORE AND AFTER PV PANEL FRAME SEALING

Location	Power (MWp)	No of panels in string	String Voltage (V)	Panel type	No. of late switch-on inverters	Inverters late switch-on becaue of Risol below 1 MΩ No. of days per month		Average switch-on time	
						Jul. 2020	Aug. 2020	Jul. 2020	Aug. 2020
Tuřany	5	14	512	FT 260-60M	15 (450kW)	31 of 31	0 of 31	10:20	7:00
Měnín	3.3	13	572	SST 175-72M	7 (70kW)	31 of 31	0 of 31	10:30	6:50
Broumov	0.4	18	666	SST 185-72M	2 (90kW)	31 of 31	0 of 31	10:30	7:10

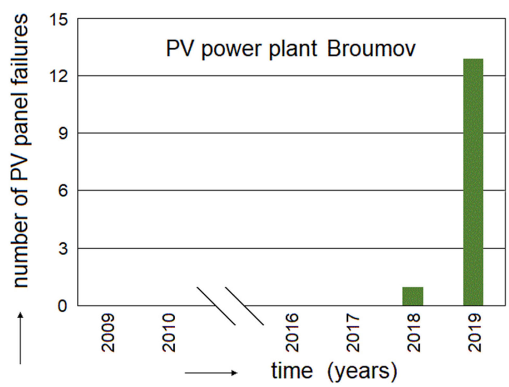


Fig. 8. Annual number of PV panel failures at Broumov location.

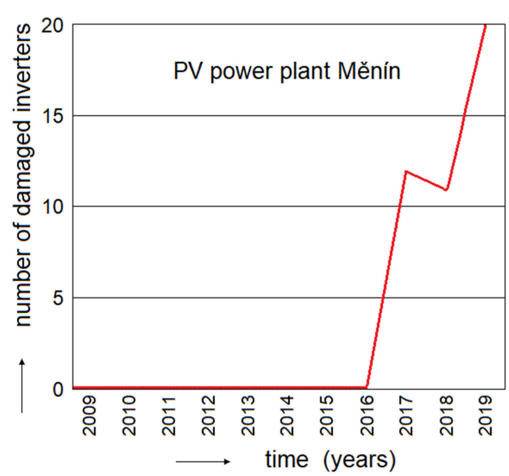


Fig. 9. Annual number of inverter failures at Menin location.

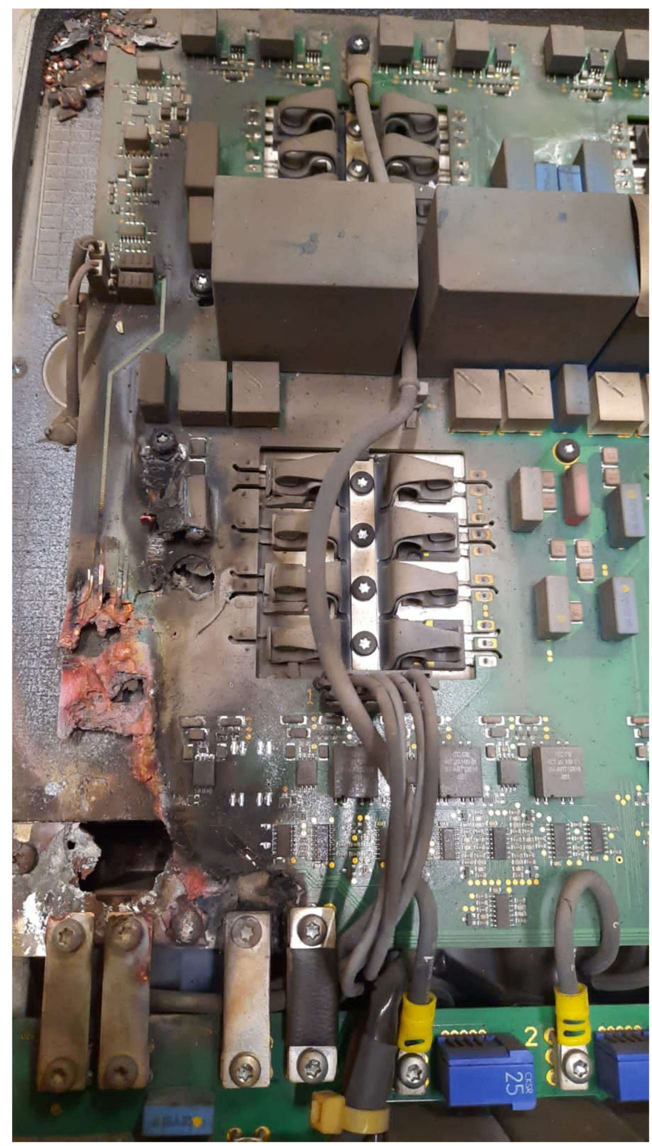


Fig. 10. Destroyed inverter SMA.

panels, just a few %, is not very high, the multiplication effect can cause a substantial reduction of energy production of the PV plant and/or substantial price increase of PV panel and stringer replacements. Similar PV panel, and subsequent PV inverter, damage, because of edge delamination effect occurs at majority of PV power plants older than ten years in the Czech Republic.

Another unwanted effect caused by Risol reduction because of edge delamination and water penetration is late morning inverter switch ON. The protection circuit of the inverter can switch on the inverter only when the Risol is increased above the threshold typically 1 MΩ.

PV panels with edge delamination (before discharge channel is created) have substantially reduced Risol in the morning until the water at the edge delamination area is dried off. It takes typically about 3 h (see Table II). It means that very substantial part of the energy produced by PV panel is lost because the inverters are not connected to the grid.

Additional sealing of the PV panel frames by siloxane gel can reduce the number of combined PV panel and PV inverter very substantially. Several inverters with late switch on effect were selected and their frames were sealed by transparent polysiloxane gel. Late switch-ON effect was eliminated completely (see Table II).

III. Conclusion

Modules produced in Asia and the Czech Republic in the year 2009 installed in the Czech Republic were investigated. The most frequent problems are connected with delamination. After ten years of operation, the number of damaged PV panels is growing substantially, mainly because of critical delamination failures. It is possible that the 25–30 years PV panel lifetime, declared by many PV panel manufacturers, is too optimistic. The system voltage of all investigated PV power plants was in the range 500–600 VDC only. It is possible that at new PV power plants with system voltage 1100–1300 VDC the critical delamination failure will occur earlier. Delamination will be even more critical in extreme climatic conditions and should be taken into account. The EVA encapsulant is low cost but not as good from the durability point of view [6]–[8]. A bit more expensive polysiloxane could be used to substantially prolong lifetime of PV panels [9]. Additional sealing of the PV panel frames by polysiloxane gel reduced the number of combined PV panel and PV inverter failures very substantially.

The highlights of this work are defined as follows.

1) Damage of PV panels and PV inverters is caused by the combination of edge delamination, water penetration into delamination area, and high string voltage.
2) Reduction of insulation resistance Risol caused by water penetration into edge delamination results in morning switch-ON delay of inverters by about 3 h in moderate climate. The number of damaged PV panels and inverters is increasing substantially in the ninth year of PV power plants operation.
3) Sealing of the edge delamination by polysiloxane gel very substantially reduces inverter daily switch-ON delay as well as number of damaged PV panels and inverters.

References

[1] E. D. Dunlop and D. Halton, “The performance of crystalline silicon photovoltaic solar modules after 22 years of continuous outdoor exposure,” *Prog. Photovolt., Res. Appl.*, vol. 14, pp. 53–64, 2006.

[2] A. Skoczek, T. Sample, and E. D. Dunlop, “The results of performance measurements of field-aged crystalline silicon photovoltaic modules,” *Prog. Photovolt., Res. Appl.*, vol. 17, pp. 227–240, 2009.

[3] F. Bandou *et al.*, “Evaluation performance of photovoltaic modules after a long time operation in Saharan environment,” *Int. J. Hydrogen Energy*, vol. 40, pp. 13839–13848, 2015.

[4] S. Kurtz, “Photovoltaic Module Reliability Workshop 2013,” Nat. Renewable Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-5200-60167, Feb. 2013. [Online]. Available: https://www.nrel.gov/docs/fy14osti/60167.pdf

[5] M. D. Kempe *et al.*, “Ethylene-Vinyl acetate potential problems for photovoltaic packaging,” in *Proc. IEEE 4th World Conf. Photovolt. Energy Convers.*, Waikoloa, HI, USA, May 2006, pp. 2160–2163.

[6] E. E. Van Dyk, J. B. Chamel, and A. R. Gxasheka, “Investigation of delamination in an edge-defined film-fed growth photovoltaic module,” *Sol. Energy Mater. Sol. Cells*, vol. 88, pp. 403–411, 2005.

[7] A. Omazic *et al.*, “Relation between degradation of polymeric components in crystalline silicon PV module and climatic conditions: A literature review,” *Sol. Energy Mater. Sol. Cells*, vol. 192, pp. 123–133, 2019.

[8] D. C. Miller *et al.*, “Durability of polymeric encapsulation materials for concentrating photovoltaic systems,” *Prog. Photovolt., Res. Appl.*, vol. 21, no. 4, pp. 631–651, 2013.

[9] V. Poulek, D. S. Strebkov, I. S. Persic, and M. Libra, “Towards 50 years lifetime of PV panels laminated with silicone gel technology,” *Sol. Energy*, vol. 86, no. 10, pp. 3103–3108, 2012.