Surge Withstand Capabilities of Photovoltaic Modules and Their Bypass Diodes under Lightning Overvoltages

Sergio Roberto Santos[1], Alexandre Piantini[2], Cleiton Busse[1], Hélio Sueta[2] and Miltom Shigihara[2]

[1]Embrastec Indústria e Comercio de Equipamentos Eletrônicos Ltda, Ribeirão Preto (Brazil)

[2]Institute of Energy and Environment of the University of São Paulo (Brazil)

Abstract

Photovoltaic (PV) system components are vulnerable to transient overvoltages caused by direct and indirect lightning and switching in the electrical grid. Therefore, for the reliability, efficiency, and safety necessary for the technical and economic feasibility of PV systems, it is essential to protect these components from transient overvoltages. These effects must be quantified through the relationship between the magnitudes of these overvoltages and the Surge Withstand Capability (SWC) value of these components, i.e., photovoltaic modules and their bypass diodes. This study presents the results of lightning impulses applied to photovoltaic modules and bypass diodes, considering the presence or absence of surge protective devices.

Keywords: Bypass Diodes, Lightning, Overvoltage, PV Modules, Surge Withstand Capability

1. Introduction

PV systems convert solar radiation - energy carried by photons - into electrical energy and are installed in open areas to maximize sunlight exposure. Because of this, they are highly susceptible to lightning. According to research conducted in Europe (Kohlenberg, 2013), lightning surges are responsible for approximately 42% of the damages to photovoltaic systems, followed by structural and material defects (~20%), animal bites (~11%), storms/snow weight (~6.5%), fire (~2%), or other damages including vandalism, theft, flooding, malfunction etc.

Many studies have analyzed the damages due to direct lightning discharges on the modules, such as those by Sueta *et al*. (2012, 2013); others consider the effects related to indirect lightning, which induce voltages in the systems through LEMPs (Lightning Electromagnetic Pulses), and can reduce the lifespan of the modules and cause damages, including component burnout (e.g., bypass diodes), (Jiang and Grzybowski, 2013, Jiang and Grzybowski, 2014; Santos *et al.*, 2023).

Despite causing more minor damage, indirect lightning effects occur more frequently than direct discharges. Lightning strikes occurring up to 2000 meters from photovoltaic systems can induce surge voltages capable of causing damage (Hasse and Wiesinger, 1993; Du *et al*, 2025). For a very long line without transformers, surge arresters, and shield wire, over a perfectly conducting plane, it is possible to estimate the maximum induced voltage peak using a formula by Rusck (1958).

This study presents an experimental analysis by simulating the effects of indirect lightning on photovoltaic modules and their possible effects, considering component permanent failure. The analysis shows how including Surge Protective Devices (SPDs) specific to photovoltaic systems affects damage variability and the voltage (magnitude and polarity) that damages the bypass diode.

The results obtained in this study allow for a better assessment of the vulnerabilities of photovoltaic modules and their bypass diodes, as well as the effectiveness of their protection through SPDs, thus contributing to greater reliability, efficiency, and safety of PV systems.

10.18086/swc.2025.03.71 Available at http://proceedings.ises.org

2. Lightning and Bypass Diodes

The PV modules commonly sold are formed by series-connected submodules, a series connection of PV cells with an anti-parallel bypass diode. The main objective of that bypass diode is to protect the submodule from operating at the second quadrant, thus avoiding its overheating and subsequent degradation due to the operation at negative voltages (Yang et al, 2012; Rodríguez et al, 2022). Among the different types of diodes, Schottky diodes have a low threshold voltage in forward bias and good switching characteristics (Shin et al, 2018). Therefore, they are widely used as bypass diodes in photovoltaic modules and can protect them even in cases of current differences (mismatches). However, they can be easily damaged by overvoltages, such as those caused by lightning, since their breakdown voltage under reverse bias is 60 to 100 V (Shin et al, 2018).

There are three conditions for a bypass diode, as described in the literature (Hamada, 2023): Possibility I, the diode operates as intended, conducting in the forward direction and blocking current in the reverse direction. Possibility II, when the diode is damaged and allows current to flow in both directions, effectively resulting in a short circuit. Possibility III, the diode does not conduct in either direction, which is equivalent to an open circuit. Although the literature often mentions the possibility of bypass diodes becoming an open circuit, ceasing to conduct electrical current entirely (Rodríguez et al, 2022), the experience of the authors of this article was limited to defective bypass diodes that had become short-circuited, allowing current to flow in both directions.

Lightning is among the main causes of photovoltaic (PV) system failures (Kohlenberg, 2013). The construction of PV systems with greater power corresponds to the increase in the area occupied by photovoltaic modules (Martzloff, 1989), increasing the exposure of these systems to lightning (Zaini, 2017). Although installing PV modules on top of a building does not increase the probability of direct strokes to the building, the vulnerability of the modules to surges caused by both direct and indirect strokes should be assessed (Pons and Tommasini, 2013).

The construction of photovoltaic (PV) systems with higher power output generally requires installing a larger number of photovoltaic modules. As the number of modules increases, their total area expands, increasing their exposure to environmental factors such as lightning. With more surface area exposed, the likelihood of lightning strikes affecting the system rises, posing potential risks to the equipment and overall system reliability.

Photovoltaic (PV) modules are fundamental components of a PV system, and their overall reliability and lifespan are important factors influencing both the PV power generation process and the investment considerations associated with PV systems (Ma, 2022). The longevity and performance of these modules, including bypass diodes, are directly connected to the economic feasibility of photovoltaic energy production, as any reduction in module efficiency shortens their useful life and may undermine the financial viability of PV installations.

The degradation of photovoltaic modules results in a loss of efficiency, ultimately impacting their operational lifespan. This efficiency reduction affects energy output and introduces uncertainties in the return on investment for PV generation projects (Ahmad et al, 2017). Therefore, having precise information regarding the degradation process of PV modules is essential for minimizing investment risks and ensuring informed decision-making in PV system deployment (Ndiaye et al, 2013).

Although lightning strikes are widely recognized as a significant cause of failures in PV systems (Jiang and Grzybowski, 2013, Jiang and Grzybowski, 2014; Coetzer et al, 2019; Santos et al, 2023), they are not typically categorized among the leading causes of failures specific to PV modules themselves. Electromagnetic coupling between lightning and PV systems can occur through three mechanisms: galvanic, magnetic, and capacitive coupling, with capacitive coupling generally producing the lowest intensity effects (Sueta et al, 2012).

PV systems are more frequently exposed to the consequences of indirect lightning strokes rather than direct strokes (Bokoro and Doorsamy, 2018). Research on induced overvoltages in PV modules indicates that the magnitudes of these overvoltages are determined mainly by the geometry of the internal conductive loops (Bokoro and Doorsamy, 2018; Damianaki et al, 2020). The vulnerability of PV systems to lightning is directly related to several factors, such as the length of cables used to interconnect system components, the absence of metal frames, and the lack of a metal cover - often aluminum - on the back of the modules (Zhang et al, 2019, 2020).

Understanding the reduction in efficiency due to degradation caused by indirect lightning strokes is vital for assessing the reliability and expected lifespan of PV systems. These considerations are of significant interest to investors and end-users, as they play a key role in determining photovoltaic installations' long-term performance and financial returns (Kim et al, 2021; Aghaei et al, 2022).

3. Methodology

3.1. Pulse applications in the modules

The investigation used photovoltaic (LSF) and high-voltage laboratory resources from the Institute of Energy and Environment of the University of São Paulo. The objective was to determine the overvoltage levels that lead to failures in photovoltaic modules or their bypass diodes, both with and without surge protective devices.

Initially, six polycrystalline silicon PV modules, referenced in Table 1, were pre-qualified through visual inspection, electroluminescence test, and insulation resistance measurement in dry and wet environments, to verify that the modules were in good condition and did not present previous failures or defects. The modules were examined through the following procedures indicated in the international standard developed by the International Electrotechnical Commission (IEC), IEC 61215, which establishes the requirements for design, qualification, and testing of crystalline silicon photovoltaic modules intended for terrestrial applications. Its main goal is to ensure the reliability, durability, and performance of solar modules throughout their lifespan:

1) Visual inspection, for checking possible visible flaws or cracks in the tested module;

2) Electroluminescence, to identify microcracks in the modules;

3) Insulation test, when a 1000 V voltage plus twice the maximum operating voltage of the PV system is applied to the module for 1 minute. Then another voltage is applied, at the maximum voltage value of the PV module, and maintained for 2 minutes. These tests aim to detect insulation faults in the module that could lead to current leakage.

After the initial test, the I-V curves of all six modules were created to obtain and record their main electrical parameters: Open Circuit Voltage (Voc), Short Circuit Current (Isc), Maximum Power (Pm), Voltage at Maximum Power Point (Vmp), Current at Maximum Power Point (Imp), Fill Factor (FF), and Cell Efficiency (Ƞ), as can be seen in Figure 1 and the values in Table 2.

Table 1: Tested modules.

Module	Material	Cell quantity
1, 2 and 3	polycrystalline silicon	36
4, 5 and 6	polycrystalline silicon	48

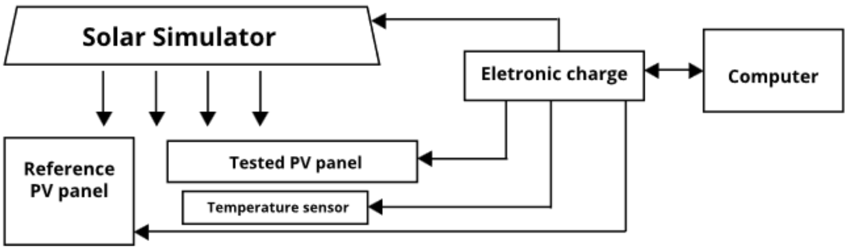

Figure 1: Solar simulator test diagram.

Table 2: Main electrical initial parameters.

Module	Voc (V)	Isc (A)	Maximum power (W)	Fill factor (%)	Cell efficiency (%)
1	22.45	8.62	143.80	74.30	16.41
2	22.65	8.65	147.94	75.55	16.89
3	22.74	8.67	151.14	76.67	17.26
4	30.184	8.71	199.21	75.77	17.05
5	30.250	8.75	197.20	74.52	16.89
6	30.431	8.89	198.74	73.51	17.01

After pre-qualifying the six modules, the following pulse sequences were applied:

- Modules 1, 2, and 3: 100 pulses of alternating positive and negative polarity, with the voltage progressively increased until the bypass diode failed;
- Module 4: 2 pulses of alternating positive and negative polarity, with the voltage progressively increased until the bypass diode failed;
- Module 5: successive positive pulses of either positive or negative polarity, with the voltage progressively increased until the bypass diode failed;
- Module 6: successive positive pulses, with the voltage progressively increased until the bypass diode failed.

The objectives of these sequences were:

Modules 1, 2, and 3: to assess whether several consecutive pulses could alter the electrical parameters of the modules, potentially affecting their usability;

Modules 4, 5, and 6: to determine whether a single pulse, based on values identified in the tests with Modules 1, 2, and 3, would be sufficient to alter the electrical parameters of the modules, and whether the pulse polarity influences this effect.

The initial goal was to evaluate the cumulative effect of repeated lightning impulses and to verify whether a single impulse at a specific voltage level could damage the module and its bypass diode. The pulse application diagram is shown in Figure 2.

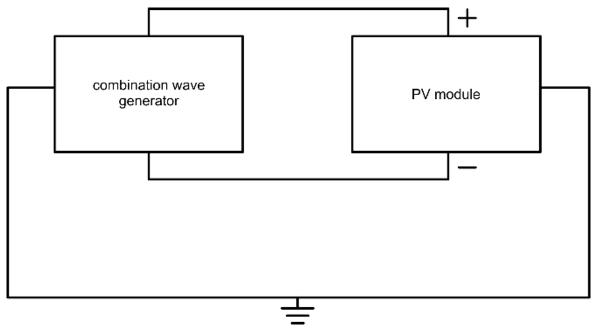

Figure 2: Setup - impulse voltage tests.

All pulses used a combined waveform comprising a 1.2/50 µs impulse voltage and an 8/20 µs impulse current. After applying the impulses, the module returned to the LSF so that a new I-V curve was obtained, and the values of its electrical parameters were compared to those recorded before the last impulses application; the variations were recorded.

3.2. Surge Protection Device tests

To assess how well the SPDs safeguard photovoltaic modules, voltage pulses were intentionally introduced. The voltage measured at the output of these devices, which reflects the voltage experienced by the photovoltaic modules themselves, provided the necessary evaluation data.

A specific SPD was used in tests for the protection of the direct current side of a photovoltaic system, whose image is in Figure 3, with the following characteristics:

- maximum continuous operating voltage (d.c.) (UC): 1500 VDC;
- nominal discharge current (8/20 µs) (In): 20 kA;
- maximum discharge current (8/20 µs) (Imax): 45 kA;
- voltage protection level (UP): ≤ 1.5 kV.

Figure 3: SPD used in the tests.

Voltage impulses with magnitudes of 1400 V, 2000 V, and 2300 V were initially applied, and the voltages across the module-SPD assembly were recorded using an oscilloscope. Figure 4 shows examples of the standard voltage and current impulses applied. The pulse application diagram and its image are in Figures 5 and 6.

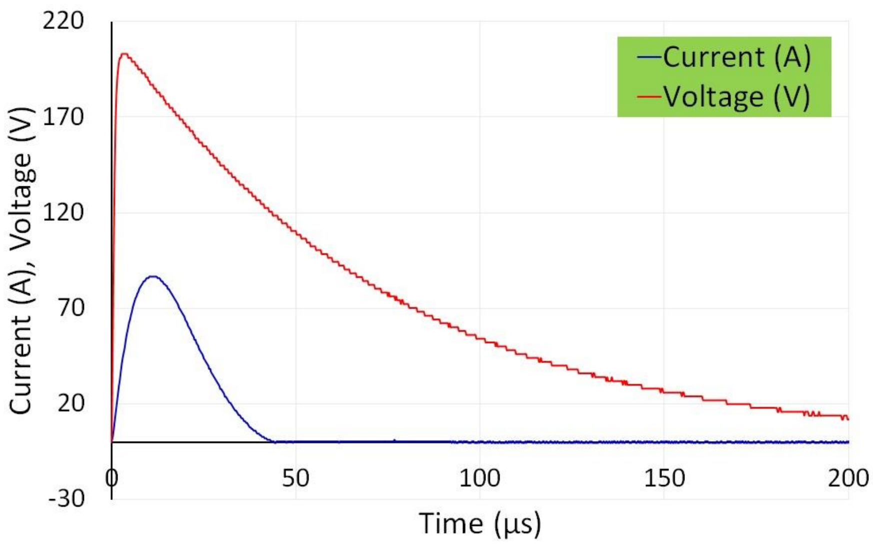

Figure 4: Combined waves – standard voltage and current impulses.

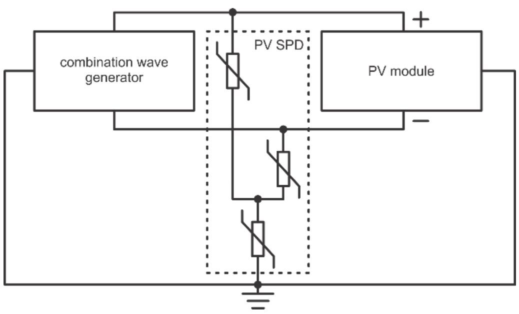

Figure 5: Setup - impulse voltage tests with SPDs.

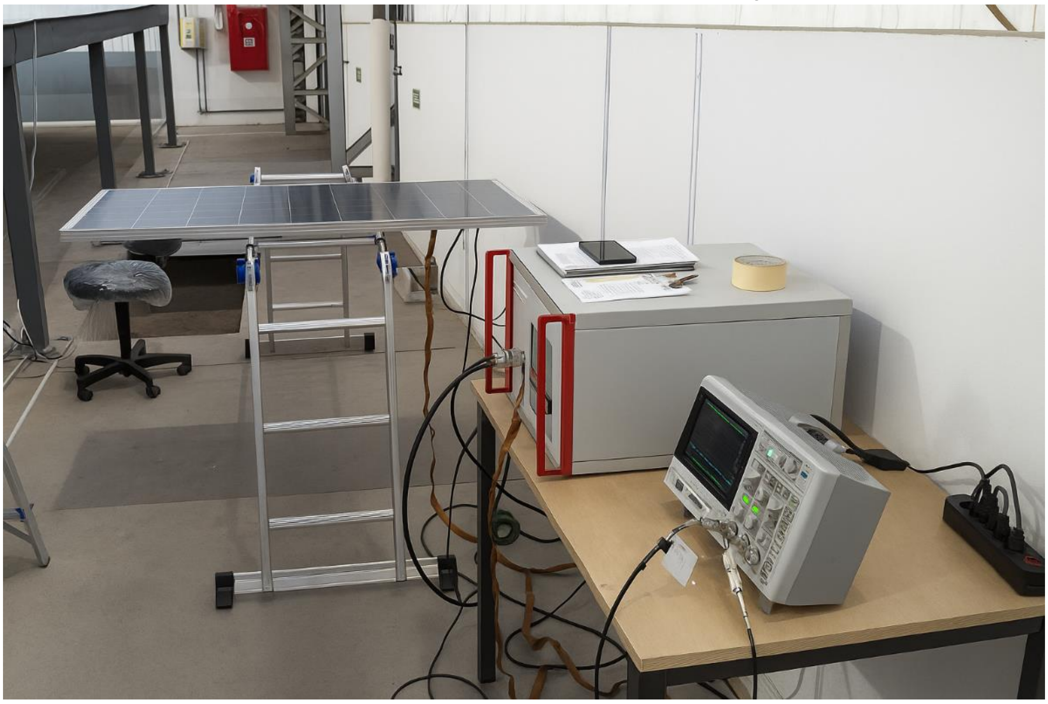

Figure 6: Setup - impulse voltage tests with SPDs.

4. Results

4.1. Results of pulse applications in the modules

Tables 3, 5, 7, 9, 11, and 13 show the pulse test sequence for each module, while Tables 4, 6, 8, 10, 12, and 14 present the consequences of the pulse applications on the modules and the bypass diodes.

Table 3: Pulses test sequence module 1.

Application	Nº Pulses	Interval between pulses (S)	Voltage (V)	Polarity	Result
1	100	10	1200	Both (+/-)	Module and diode in good condition
2	100	10	1300	Both (+/-)	Module and diode in good condition
3	100	10	1400	Both (+/-)	Module in good condition and the diode bypass destroyed
4	100	10	1500	Both (+/-)	Module in good condition, without a diode bypass

Table 4: Module 1 parameters.

Application	Voc (V)	Isc (A)	Maximum power (W)	Fill factor (%)	Cell efficiency (%)
0	22.45	8.62	143.80	74.30	16.41
1	22.48	8.58	142.69	17.70	16.29
2	22.50	8.63	143.70	17.73	16.40
3	21.80	8.68	135.40	-	-
4	22.43	8.54	141.45	73.83	16.15

Table 5: Pulses test sequence module 2.

Application	Nº Pulses	Interval between pulses (S)	Voltage (V)	Polarity	Result
1	100	10	200	Both (+/-)	Module in good condition, without a diode bypass
2	100	10	1500	Both (+/-)	Module in good condition, without a diode bypass
3	100	10	2500	Both (+/-)	Module in good condition, without a diode bypass
4	100	10	3500	Both (+/-)	Module in good condition, without a diode bypass

Table 6: Module 2 parameters.

Application	Voc (V)	Isc (A)	Maximum power (W)	Fill factor (%)	Cell efficiency (%)
0	22.65	8.65	147.94	75.55	16.89
1	22.67	8.64	147.78	75.44	16.87
2	22.63	8.63	146.89	75.28	16.77
3	22.64	8.63	147.04	75.23	16.78
4	22.62	8.58	146.24	75.34	16.69

Table 7: Pulses test sequence module 3.

Application	Nº Pulses	Interval between pulses (S)	Voltage (V)	Polarity	Result
1	100	10	220	Both (+/-)	Module in good condition, without a diode bypass
2	100	10	750	Both (+/-)	Module in good condition, without a diode bypass
3	100	10	1750	Both (+/-)	Module in good condition, without a diode bypass
4	100	10	2750	Both (+/-)	Module in good condition, without a diode bypass

Table 8: Module 3 parameters.

Application	Voc (V)	Isc (A)	Maximum power (W)	Fill factor (%)	Cell efficiency (%)
0	22.74	8.67	151.14	76.67	17.26
1	22.72	8.69	150.99	76.49	17.24
2	22.84	8.66	151.21	76.43	17.26
3	22.6	8.84	150.10	-	-
4	22.72	8.61	149.32	76.31	17.05

Table 9: Pulses test sequence module 4.

Application	Nº Pulses	Interval between pulses (S)	Voltage (V)	Polarity	Result
1	2	-	1400	Both (+/-)	Module in good condition, diode by-pass destroyed
2	2	-	2000	Both (+/-)	Module in good condition, without a diode bypass

Table 10: Module 4 parameters.

Application	Voc (V)	Isc (A)	Maximum power (W)	Fill factor (%)	Cell efficiency (%)
0	30.184	8.710	199.210	75.77	17.05
1	30.231	8.762	198.011	75.60	17.06
2	30.214	8.764	200.850	75.85	17.19

Table 11: Pulses test sequence module 5.

Application	Nº Pulses	Interval between pulses (S)	Voltage (V)	Polarity	Result
1	1	-	1400	-	Module and bypass diode in good condition
2	1	-	1400	+	Module and bypass diode in good condition
3	1	-	2000	-	Module and bypass diode in good condition
4	1	-	2000	+	Module in good condition, diode by-pass destroyed
5	1	-	2000	+	Module in good condition, without a diode bypass

Table 12: Module 5 parameters.

Application	Voc (V)	Isc (A)	Maximum power (W)	Fill factor (%)	Cell efficiency (%)
0	30.250	8.750	197.26	74.52	16.89
1	30.254	8.811	198.79	74.58	17.02
2	30.316	8.799	199.33	74.72	17.06
3	30.07	8.701	198.40	74.90	17.00
4	30.263	8.717	197.88	75.01	16.94
5	30.183	8.809	198.10	74.85	17.04

Table 13: Pulses test sequence module 6.

Application	Nº Pulses	Interval between pulses (S)	Voltage (V)	Polarity	Result
1	1	-	1400	+	Module in good condition, diode by-pass destroyed
2	1	-	2000	+	Module in good condition, without a diode bypass

Table 14: Module 6 parameters.

Application	Voc (V)	Isc (A)	Maximum power (W)	Fill factor (%)	Cell efficiency (%)
0	30.431	8.885	198.75	73.51	17.01
1	30.451	8.931	200.24	73.62	17.14
2	30.451	8.931	200.24	73.62	17.14

4.2. Surge Protection Device test results

The test results, illustrated in Figure 7, demonstrate that the SPDs are effective in limiting the overvoltages at the terminals of the modules and bypass diodes. However, this mitigation is insufficient to prevent bypass diode failure.

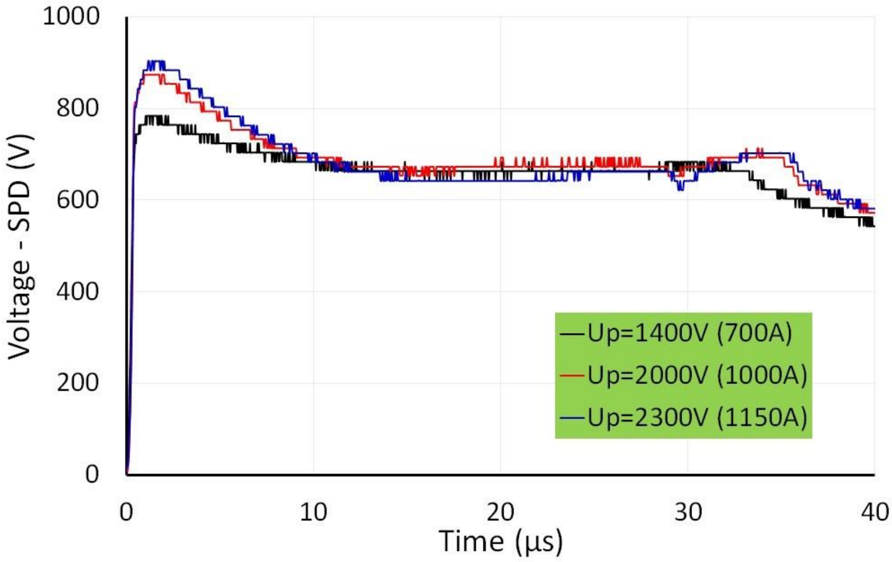

Figure 7: Testing voltage impulse levels at the SPD (peak values Up indicated in the legend).

5. Conclusion

This work studied the transient overvoltage’s effect on PV modules, presenting values that cause permanent damage to their bypass diodes and the modules themselves. It also evaluated the efficiency of specific SPDs in protecting photovoltaic modules. The study on transient overvoltages reveals critical insights into their impact on PV modules and the effectiveness of SPDs in providing necessary protection. The results show that the vulnerability of the photovoltaic module and bypass diode set depends on limiting the magnitude of the transient overvoltages across the bypass diode, since the module itself has much greater withstand voltage capability. To address this, SPDs can be installed to keep overvoltage magnitudes within tolerable levels for bypass diodes.

The results also showed that bypass diodes can exhibit different withstand capabilities when forward or reverse biased, which makes it necessary for their datasheets to include the withstand values for both situations, so that the SPDs are specified appropriately for them.

Through the study, it was also possible to observe the importance of easy access to bypass diodes to conveniently inspect and, if necessary, replace them. This can significantly reduce downtime in photovoltaic systems, thereby contributing to greater operational efficiency and extending the lifespan of the equipment.

The study also demonstrated the effectiveness of protecting modules with SPDs, limiting the value of transient overvoltage at their terminals. Although the installation of SPDs is mainly used to protect inverters and, secondarily, modules, they should also be used to protect bypass diodes.

Future research in photovoltaic system protection should focus on two key areas: evaluating the durability of bypass diodes under transient overvoltage conditions and identifying best operational practices to enhance their resilience; and determining the optimal placement and functional roles of SPDs within the system to maximize reliability and safety.

6. Acknowledgments

The authors thank the Institute of Energy and Environment of the University of São Paulo and Embrastec for the materials and laboratories used in this work.

7. References

Aghaei M.; Fairbrother, A.; Gok, A.; Ahmad, S.; Kazim, S.; Lobato, K.; Oreski, G.; Reinders, A.; Schmitz, J.; Theelen, M.; Yilmaz, P.; Kettle, J.; Review of degradation and failure phenomena in photovoltaic modules. Renewable and Sustainable Energy Reviews, 2022. DOI: 101016/j.rser.2022.112160.

Ahmad N. I.; Kadir, Z.; Izadi, M.; Azis, N.; Radzi M. A. A.; Zaini, H. Nasir, S. Lightning protection on photovoltaic systems: A review on current and recommended practices. Renewable and Sustainable Energy Reviews, 2017. DOI: 10.1016/j.rser.2017.07.008.

Bokoro P and Doorsamy W. Investigation of lightning surge effects on a grid-connect PV plant. 2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE), pp.1-4. September 2018.

Coetzer K. M., Wiid P. G. and Rix A. J. Investigating lightning induced currents in photovoltaic modules. International symposium on electromagnetic compatibility. Proceedings. Barcelona. 2019.

Damianaki K.; Christodoulou, C. A.; Kokalis, C. C. A. ; Kyritsis, A.; Ellinas, E. D.; Vita, V.; Gonos, I. F. Lightning protection of photovoltaic systems: Computation of the developed potentials. Applied Sciences.2020. DOI: 10.3390/app11010337.

Du, Z.; Ding, Y.; Du, Y. ; Yeung, C. ; Chen, H.; Zhang, S. Indirect Lightning Strike Analysis of Blocking Diodes in a Large-Scale Photovoltaic System. 13th Asia-Pacific International Conference on Lightning (APL).

Hamada, T.; Nanno, I.; Ishikura, N.; Fujii, M.; Oke, S. Breakdown Characteristics of Schottky Barrier Diodes Used as Bypass Diodes in Photovoltaic Modules under Lightning Surges. Energies 2023, 16, 7792. https://doi.org/10.3390/en16237792.

Hasse. P.; Wiesinger J. EMV Blitz-Schutzzonen-Konzept. Munique. Alemanha. Pflaum Verlag.1993.

Jiang, T.; Grzibowski, S. Impact of Lightning Impulse Voltage on Polycrystalline Silicon Photovoltaic Modules. In: International Symposium on Lightning Protection. 2013, Belo Horizonte. Proceedings. Belo Horizonte. 2013.

Jiang, T.; Grzybowski, S. Electrical Degradation of Photovoltaic Modules Caused by Lightning Induced Voltage. In. Electrical Insulation Conference. Pennsylvania. 2014.

Kim, J.; Rabelo, M.; Padi, S, P.; Yousuf, H.; Cho E.C.; Yi J. A review of the degradation of photovoltaic modules for life expectancy. Energies 2021. https://doi.org/10.3390/en14144278.

Kohlenberg, R. Entwicklung bei schadensfällen aus sicht der versicherung. Manheimer Versicherung AG. Freiburg. January 2013.

Martzloff F. D. Lightning and surge protection of photovoltaic installations. National Institute of Standards. U.S Department of Commerce. June 1989.

Ma, M.; Ma, J.; Wang, H.; Ma, W.; Zhang, R. PV module life prediction based on coupled failure model. Microelectronics Reliability. Volume 138, November 2022.

Ndiaye A., Charki A., Kébe C. M. F., Kobi A., Ndiaye P.A. and Sambou V. Degradations of silicon photovoltaic modules: A literature review. Solar Energy. Vol. 96, October. 2013, pp. 140-151.

Pons E. and Tommasini R. Lightning protection of pv systems. 4th International Youth Conference on Energy. Siófok, Hungary, 2013, pp.1-5.

Rodríguez, J. D. B; Paja, C. A. R; Garcés, S. I. S. Improved modelling of bypass diodes for photovoltaic applications. Alexandria Engineering Journal. 2022. Nº61, pgs 6261-6273.

Romênia G. Vieira, Fábio M. U. de Araújo, Mahmoud Dhimish and Maria I. S. Guerra. A Comprehensive Review on Bypass Diode Application on Photovoltaic Modules. Energies, May14, 2020. doi:10.3390/en13102472. Available:< https://www.mdpi.com/1996-1073/13/10/2472>.

Rusck S., Induced lightning overvoltages on power transmission lines with special reference to the overvoltage protection of low voltage networks. Transactions of the Royal Institute of Technology, Stockholm, No. 120, 1958.

Santos, S; Piantini, A; Shigihara, M., "An Investigation into the Effects of Lightning-induced Transients on the Degradation of PV Modules Performance," In: 2023 International Symposium on Lightning Protection (XVII SIPDA), Suzhou, China, 2023, pp. 1-5, Doi: 10.1109/SIPDA59763.2023.10349190.

Smit H. C. Investigating surge protection and earthing designs used for utility-scale PV plants. Faculty of Engineering, Stellenbosch University, 2021, 107p.

Sueta, H. E.; Zilles, R.; Mocelin, A.; Santos, S.; Boemisel, E., "Experimental Verifications in Photovoltaic Modules Subject to Current Impulses for Simulation of Lightning Discharges," In: International Conference on Grounding and Earthing & 5th International Conference on Lightning Physics and Effects, 2012. Bonito, Brazil. 2012.

Sueta, H. E.; Mocelin, A.; Zilles, R.; Obase, P. F.; Boemeisel, E., "Protection of Photovoltaic Systems Against Lightning," In: International Symposium on Lightning Protection, 2013, Belo Horizonte. Proceedings. Belo Horizonte, 2013. June 2025. DOI: 10.1109/APL65034.2025.11108897.

Vieira, R.G.; de Araújo, F.M.U.; Dhimish, M.; Guerra, M.I.S. A Comprehensive Review on Bypass Diode Application on Photovoltaic Modules. Energies 2020. https://doi.org/10.3390/en13102472.

Wolfgang Mühleisen, Martin Brückner, Lukas Neumaier. Investigation of Schottky bypass diodes from a faulty PV plant. Science and Technology for Energy Transition 79, 18 (2024). https://doi.org/10.2516/stet/2024011.

Woo Gyun Shin, Suk Whan Ko, Hyung Jun Song, Young Chul Ju, Hye Mi Hwang, Gi Hwan, Kang. Origin of Bypass Diode Fault in c-Si Photovoltaic Modules: Leakage Current under High Surrounding Temperature. 12 September 2018. Energies 2018, 11, 2416; doi:10.3390/en11092416.

Yang, H.; Wang. H.; Wang, M. Investigation of the Relationship between Reverse Current of Crystalline Silicon Solar Cells and Conduction of Bypass Diode. Hindawi Publishing Corporation International Journal of Photoenergy. Volume 2012, Article ID 357218, 5 pages. Doi: 10.1155/2012/357218.

Zaini N. H. et al. Lightning surge analysis on a large scale grid-connected solar photovoltaic system. Energies, 2017. 10. 2149.

Zhang Y., Chen H., and Du Y. Lightning protection design of solar photovoltaic systems: Methodology and guidelines. Electric Power Systems Research. June 2019. 174.

Zhang Y., Chen H. and Du Y. Considerations of photovoltaic system structure design for effective lightning protection. IEE Transactions on Electromagnetic Compatibility. May 2020. pp.1-9.