

Lightning Protection of Rooftop Photovoltaic Systems: A Scientific Approach

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Abstract— The increasing of photovoltaic microsystems in Brazil follows global trend for low-cost panels and efficient cells. Although the solar modules are located on roofs and lightning strikes can damage all components of PV System (PVS). The Lightning Protection Systems (LPS) associated with Surge Protection Device (SPD) are the effective protection against electromagnetic effects. This study estimated the values of overvoltage and overcurrent induced by lightning in 2.65 kW PVS under different configurations, with or without LPS, by Faraday's Law of Induction. The estimation of the difference of potential on soil is according to the Law of Ohm and Maxwell equation. Thus, the purpose of this publication is to support the LPS design and SPD specification for PVS. The simulation considered the DC wiring design, distances from LPS and tilt angle of solar modules. The results pointed out that impulse rate of 200 kA/μs induces peaks up to 201,6 kV and 28,3 kA in DC circuits by lightning strikes and up to 82 kV in AC terminals of DC/AC converter transferred from soil by grounding systems. In conclusion, the main protection system against lightning damages is LPS associated with SPD that can protection against abnormal values of induced voltage and current. In addition, equipotentialization is necessary to complement the effective protection using a unique grounding system in accordance with the guidelines of the international standards IEC and ABNT.

I. INTRODUCTION

The photovoltaic systems generally installed on the top of houses and buildings make them susceptible to lightning strikes and their electromagnetic direct and indirect effects. In addition, abnormal electrical current or atmospheric discharges can damage all solar modules and electronic devices during the course to the grounding system. Thus, installations, equipment and even electric vehicles connected to charging stations, may suffer severe damage during the occurrence of this natural phenomenon. In

addition, the evaluation of economic losses have to compute the costs to repair the equipment and installations, as well as the energy not generated during the repairing period of the system and its restarting operation.

Therefore, lightning is a worldwide problem. For example, Brazil has experienced an average of 78 million lightning strikes per year [1]. Statistical surveys researched pointed out that at least 30% of the damage in photovoltaic systems of Germany is by lightning [2] and almost 70% in systems of Malaysia [3]. Therefore, electrical and

electronic systems and equipment in both residential and industrial sectors require appropriate protective procedures to reduce or to eliminate the effects of transients in electrical circuits by overcurrent and overvoltage [4].

According to Law of Magnetic Induction (Faraday), the electrical discharges produced by electromagnetic surges can induce currents and voltages in electrical systems, and, in its turn, the lightning protection methods aim to neutralize or reduce the damage to an acceptable level. The risk is directly proportional to the characteristics of the discharge, such as the peak value or the intensity of the electric current, duration, impulse rate (di/dt) and thermal energy or integral of Joule [5,6]. Thus, the performance of a lightning protection system may consider the efficiency formed by the set lightning mesh (electrode), surge protection device (SPD), grounding and equipotentialization system [7].

In addition, a mathematical model of PV system can simulate the effects of lightning strikes using PSCAD/EMTDC Computer Tool. The goal of such research was to estimate transients as induced currents and voltages in electrical circuit of the PV system. The results show that a transient of current will appear at the nearest point to the lightning strike and in same value of lightning current and the transient of voltage will appear at any point in AC side, which can damage the AC/DC converter. In addition, the paper intended to subsidize the performance of project to lightning protection system (LPS) in PV system [8].

A deeper research has investigated and solved complaints about damaged in PV systems of customers due to lightning strikes on power distribution network (electrical utilities) in Malaysia. The study investigated permanent and momentary interruptions in distribution network as consequence of atmospheric disturbance. It used a rooftop system (3.91 kWp) modelled by PSCAD/EMTDC Tool for computational simulations in the Centre for Electromagnetic and Lightning Protection Research (CELP) of the Universiti Putra Malaysia for providing facilities and scientific assistance in experiments. The simulation included several configurations of the PV systems simulating with or without application of lightning protection system (LPS) and surge protection device (SPD) [3].

Over the last years, the need to understand the electromagnetic effects in electronics devices and electrical circuits of photovoltaic systems demanded multidisciplinary efforts aiming to produce valuable data for manufacturers and suppliers of PVS projects [9]. Among these investigations, one proposed an extensive review about fault characteristics of DC micro grids

(DCMGs) and the protection challenges with a proposition for innovative protection techniques to solve these issues and enhancement of the protection of DCMGs [10]. For example, the analysis of reductions in backflow lightning overvoltage in PVS power plant at Ta'if city (KSA) has used high-frequency models for computational simulation to design a modified grounding system to decrease the lightning overvoltage effects in similar PVS [11].

On the other hand, partial element equivalent circuit (PEEC) method with vector fitting technique has analyzed lightning transients in PV systems, taking into account the frequency-dependent effects and ferromagnetic properties steel-structures [12]. Another paper has developed a new model of system for fault protection in AC micro grids having multiple grounding system, with communication-supported digital relays in different protection modules [13]. Other study has proposed a single-phase three-wire grid-connected power converter (STGPC) with energy storage for positive grounding photovoltaic generation system (PGPGS) where no transformer was required even for PGPGS with low-voltage battery set [14]. Thus, many studies have simulated impulsive voltages ($1.2/50 \mu s$) on polycrystalline silicon modules with reduced models with the peak voltages of 15 V, 30 V and 90 V, considering lightning strikes with positive polarity [15].

In general, results proved the occurrence of degradation in photovoltaic modules, DC to AC power converters and other electronic equipment of the photovoltaic systems due to electromagnetic effects. The efficiency degradation of polycrystalline silicon photovoltaic module (6 V - 1.5 W) by induced voltage from lightning was verified by simulation of 3,000 pulses with 1,000 V, $1.2/50 \mu s$ waveform and positive polarity, and the outputs proved strong degradation of the electrical characteristics (energy) of the photovoltaic module by impulse voltage (test) during the simulation with the discharges [16]. A second research of such authors detected the exponential decrease of the maximum power point (MPPT) during tests on the same modules exposed to electromagnetic fields simulating effects of lightning [17].

The method of finite-difference in time-domain can simulate the performance of grounding system of SFV under direct lightning strike [18]. The method of the finite elements in the modeling 2D applying to arrangement dipole-dipole can design a system model for estimation of resistivity of geologic layers with minimum errors [19]. A grounding system designed for the safety and dispersion of lightning current in the soil depends on the type of soil and arrangement of modules [20].

The grounding system of electrical installations of photovoltaic plants must consider the electromagnetic

compatibility of electronic equipment (DC/AC converters), including the rated overvoltage or threshold [21]. Insulated power cables for high voltage proposed as down conductor for lightning arresters in LPS as preventive method against structural damage [22]. The finite-element method can analyze the electrical potential and risks related to touch and step voltages during lightning strikes in buildings with rooftop PVS [23].

The theory of Electric Field Deflection (EFD) can subsidize the position of lightning rods (captors) for best protection performance of photovoltaic systems [24]. The capacitance feature (electric field) can provide non-touch or remote measure of voltage without direct contact with an energized conductor [25]. Moreover, the equipotentialization can eliminates or minimizes the ground potential difference to protect people from electrical shock and prevent damage in power system and equipment [26].

In turn, also the international standards directives determine the calculation of the intensity of the magnetic field inside buildings creating internal lightning protection zones (LPZ) as rated safety zones or levels of protection for risk assessment of electronic systems against the effects from lightning electromagnetic impulses (LEMP). However, to external installations located on the roof of buildings, on the contrary, the standard recognizes the greater susceptibility to the direct effects of atmospheric discharge and its non-attenuated magnetic fields where there is greater possibility of damage to PV systems [27,28].

This paper shows a complementary methodology using fundamental laws of electromagnetism and Ohm's theory to subsidize the checking of risk management determined by international standards IEC-62305/2020 and NBR-5419/2015 related to protect photovoltaic systems against lightning damages. Thus, the method proposed has estimated the induced voltages and currents by lightning strikes in PV systems installed in buildings, with or without lightning protection system [29]. In addition, to complete the analysis the methodology has quantified the grounding effects by estimating the values of overvoltage in equipment and building facilities caused by grounding systems. The results has analyzed the performance of grounding grids and equipotentialization projects [26].

II. MATHEMATICAL MODELING

As shown in Fig. 1, the photovoltaic system with surge protection device (SPD) represents two scenarios for case studies, the case one S1 consider flashes striking the (LPS) and the second case S2 the discharge strikes on modules of the photovoltaic system. In both cases, the atmospheric

discharge makes the direct current (DC) and unshielded electrical conductors experience the effects of electromagnetic induction, generating overvoltage and overcurrent in the electrical circuit that connects the photovoltaic modules to the energy converter DC/AC. The method of calculation also consider the estimation of the values of induced voltage and current in common and differential mode [29]. In fact, we can obtain several results by changing some parameters into a range of values in the math equations, looking for the simulation on real requirements of the system.

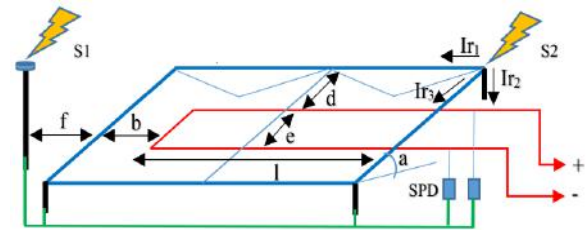


Fig. 1: Lightning strikes LPS (S1) or solar module (S2)

The second part of the study includes the application of the first and second Law of Ohm for soil modeling estimating the grounding resistance value and electrical potentials starting from grounding mesh generated by lightning flashes [26]. The magnetic induction calculation considered the fundamental Maxwell Equation of Electromagnetics [30].

a. Induction model for flashes on LPS

The S1 scenario has considered the strike of the discharge on the lightning rod causing the induction of electrical voltages UIP in non-shielded electrical circuits and structures of the photovoltaic system, estimated by math equations (1) and (2) [29].

$$U_{IP} = K_C \cdot L_M \cdot \frac{di}{dt} \quad (1)$$

Where K_C is the current division coefficient between the descending conductors in the LPS ($K_C = 1$ for one downward conductor, 0.5 for two and 0.44 for 3 or more). The di/dt is the rate of change of the current (200, 150 and 100 kA/ μ s depending on the Level of Protection against lightning - LP). Moreover, L_M is the mutual inductance between the downward cable of LPS and the loop of the electrical circuit calculated according to expression (2):

$$L_M = 0.2 \cdot m \cdot \sin(a) \cdot \ln\left(\frac{f+b+l}{f+b}\right) \quad (2)$$

Whereas m is the width of loop ($m = e$, for differential mode or $m = e + d$, for common mode), f is the minor distance between LPS and structure of array modules, l is the total length of the system and a is the tilt angle of the solar modules.

b. Induction model for flashes on solar array

The S2 scenario has considered the direct strike of lightning in the modules of photovoltaic system, causing induction of voltage U_{IP} and electrical current I_{SC} in non-shielded electrical circuits and structures of the photovoltaic system, applying equations (1), (3), (4) and (5) [29]:

$$L_M = 0.2 \cdot l \cdot \ln\left(\frac{d + e + r}{d + r}\right) \quad (3)$$

Where r is the radius of circumference equivalent to the total area of the PV system (metallic structure for support).

The induced short-circuit current I_{SC} is estimated by equations (3) to (5), whereas L_S is the self-inductance and consider in equation (4) the current of lightning I must be divided by 3, considering the three possible flow paths of the current to earth by [29]:

$$I_{SC} = K_C \cdot I \cdot \left(\frac{L_M}{L_S}\right) \quad (4)$$

Where I is the peak of lightning current (200, 150 or 100 kA, according to Level of Protection against lightning - LP) and L_S is the self-inductance as in (5):

$$L_S = 0.8\sqrt{l^2 + e^2} - 0.8(l + e) + 0.4l \ln\left(\frac{2e/r}{1 + \sqrt{1 + (e/l)^2}}\right) + 0.4e \ln\left(\frac{2l/r}{1 + \sqrt{1 + (l/e)^2}}\right) \cdot 10^{-6} \quad (5)$$

The math expressions (1) to (5) can support the methodology of risk assessment determined by international standards and can improve the performance of the project of lightning protection systems related in IEC-62305/2020 and NBR-5419/2015 standards.

c. Model for ground potential difference

The theory of electromagnetism for ground mathematical model considers the injection of electric current in earth will generate electrical potentials that can be represented by the equation of Laplace (6), considering a conservative field [30]:

$$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \quad (6)$$

Considering the interaction vector of electric potential in the three-dimensional axes of ground, the equation of Laplace (6) results in the expression (7):

$$\Delta V = 0 \quad (7)$$

Where V is the value of electrical potential of a point referenced to the infinity and in constant resistivity soil. Moreover, Δ is the Laplace-Beltrami operator or second order differential operator.

When flash strikes over lightning protection system (LPS) and the overcurrent get down to the ground, there will be an omnidirectional spread of electrical charges in

all radial directions, starting from the grounding mesh and causing potential differences in the surface of the soil. The Fig. 2 demonstrates the voltage drop U_{AB} from a ground rod in format of decreasing exponential curve, corresponding the electrical resistance R_{AB} of the volume of soil and considering the potential 0.0 V at a point in infinity.

The model in study, Fig. 2, has considered the spreading of all electrical charges of the flash current only in the first earth layer whose depth is equivalent to the length l of the ground stick and in a ground with constant value of electrical resistivity ρ .

The dispersion of lightning current happens perpendicularly to the area of the cylindrical surfaces of the soil. In last, the first one Ohm's Law ($U_{AB} = R_{AB} \cdot I_R$) was applied to calculate the voltage drop or potential difference between two points of the ground.

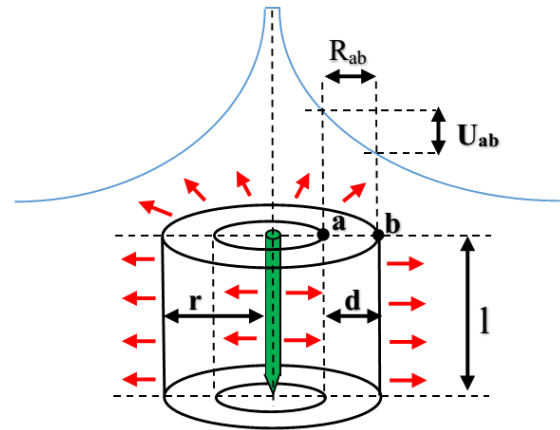


Fig. 2: Ground potential difference for single bar

In addition, for the estimation of the electrical resistance R_{AB} equivalent to the volume of ground formed between two consecutive and concentric cylinders, it applies the second Ohm's Law as expression (8) [26]:

$$R = \frac{\rho \cdot d}{2 \cdot \pi \cdot r \cdot l} \quad (8)$$

Where ρ is the electrical resistivity of ground, d is the distance between two consecutive cylindrical surfaces S_A and S_B , r is the radial distance from ground bar to the surface of external cylinder, and l is the thickness of the ground layer that is the same length of the rod.

III. RESULTS AND DISCUSSION

The scenario for simulation consists of a 2.65 kWp PV System composed with 10 solar modules of 1.65 x 0.99 m, each, as shown in Fig. 1 and considering the installation on the top of a building whose lightning protection system (LPS) has only one down conductor ($K_C = 1$).

a. Inductions by flashes on LPS

The values in Tab. 1 to 4 are the results using equations (1) and (2), corresponding to the S_1 scenario in Fig. 1 where the lightning strikes over the LPS. The results represent the values of induced voltages in DC wiring of PVS without electromagnetic shielding, with insulation-thickness of 1.50 mm and l cable length is 10.0 m. The calculations also considered the differential U_{IP-D} and common U_{IP-C} modes, and the simulation of several scenarios ranging parameters in equations (1) and (2):

- Distance of down conductor (LPS) to PVS structure.
- Rate of current impulse (200 and 100 kA/ μ s).
- The tilt angle α for solar modules inclination.
- Design C_1 : The + and – electrical wires routed together and along the edge of the solar modules.
- Design C_2 : The + and – wires is tracked together and in middle of modules.
- Design C_3 : The + and – cables put separated and put in opposite edges of the modules.

The results were calculated per unit of length and the induced voltages varies in direct proportion with variation of the tilt angle α , and the rate of current impulse (kA/ μ s). Respectively, according to the tilt angle limits of the modules, range 0° to 90° , the values of inductions varies from zero volts to maximum value given by a sinusoidal equation (1). Also, the induced values were inversely proportional with variation of distance f . However, the induced voltages varied in a greater rate by variation of α angle than the reduction in distance f . Therefore, variations of 100% in distance and angle has changed about - 21% and + 99% in the induced voltages, respectively. In addition, designs C_1 , C_2 and C_3 has demonstrated the best and worst ways to install DC cables that are modes C_1 and C_3 , respectively. At last, the increasing in length l of DC cables implies direct increase in inductions values. Thus, the results of Tables 1 to 4 can be useful to improve the performance of LPS and SPD before installing a solar PV system.

Table 1 – Induced Voltages for $f = 2.00$ m and $\alpha = 13^\circ$

Level of Protection				200 kA/μs		100 kA/μs	
Design of Circuit	e (mm)	d (mm)	DC	Uip-d (kV/m)	Uip-c (kV/m)	Uip-d (kV/m)	Uip-c (kV/m)
	C1	3	1.5	0.0024	0.0036	0.0012	0.0018
	C2	3	825	0.0024	0.6670	0.0012	0.3335
	C3	1,650	1.5	1.1413	1.1423	0.5707	0.5712

Table 2 – Induced Voltages for $f = 1.00$ m and $\alpha = 13^\circ$

Level of Protection				200 kA/μs		100 kA/μs	
Design of Circuit	e (mm)	d (mm)	DC	Uip-d (kV/m)	Uip-c (kV/m)	Uip-d (kV/m)	Uip-c (kV/m)
C1	3	1.5		0.0032	0.0049	0.0016	0.0024
C2	3	825		0.0032	0.8925	0.0016	0.4462
C3	1,650	1.5		1.5271	1.5285	0.7635	0.7642

Table 3 – Induced Voltages for $f = 2.00$ m and $\alpha = 6.50^\circ$

Level of Protection				200 kA/μs		100 kA/μs	
Design of Circuit	e (mm)	d (mm)	DC	Uip-d (kV/m)	Uip-c (kV/m)	Uip-d (kV/m)	Uip-c (kV/m)
C1	3	1.5		0.0012	0.0018	0.0006	0.0009
C2	3	825		0.0012	0.3356	0.0006	0.1678
C3	1,650	1.5		0.5743	0.5749	0.2872	0.2874

Table 4 – Induced Voltages for $f = 1.00$ m and $a = 6.50^\circ$

Level of Protection				200 kA/ μ s		100 kA/ μ s	
Design of DC Circuit	e (mm)	d (mm)		Uip-d (kV/m)	Uip-c (kV/m)	Uip-d (kV/m)	Uip-c (kV/m)
C1	3	1.5		0.0016	0.0024	0.0008	0.0012
C2		3	825	0.0016	0.4491	0.0008	0.2246
C3		1,650	1.5	0.7685	0.7692	0.3842	0.3846

b. Inductions by flash in solar array

As shown in Fig. 1, the Tab. 5 presents the results of equations (1), (3), (4) and (5) considering the S_2 scenario of PV system with direct and full lightning strike on the structure of solar array. The results represent the values of induced voltages and currents in DC wiring of PVS without electromagnetic shielding, insulation-thickness of 1.50 mm and length l is 10.00 m. The magnitude of U_{IP} voltage is in common mode and I_{IP} current in 10/350 μ s impulse rate. The simulations did not include variations in tilt angle of the solar modules and the f distance from LPS to PV system, as it did not influence the results of the induction estimations. The overvoltage estimated per unit length and the simulation has considered some designs varying the following parameters:

- The peak of current impulse (200 and 100 kA/ μ s).
- Designs C_1 to C_3 , already described before.

The inductions varied in direct and proportional way according to the variation of impulse rate (kA/ μ s). Furthermore, the analysis of the three designs pointed out the best and worst situation for installing DC cables are in C_2 and C_3 modes, respectively. The increase in the length l of the DC cables implies in direct and proportional increase to induced voltages and currents in wiring. Thus, the results of Tab. 5 can be the basis for choosing the class of the surge protection device (SPD) for PV systems. The information of this paper can be useful to improve the performance of the lightning protection system before installing a solar PV system.

Table 5 – Induced Voltages and Currents (flashes on array)

Level of Protection				200 kA/ μ s		100 kA/ μ s	
Design of DC Circuit	e (mm)	d (mm)		Uip Isc (kV/m) (kA)		Uip Isc (kV/m) (kA)	
C1	3	1.5		0.026	0.006	0.013	0.003
C2		3	825	0.019	0.005	0.009	0.002
C3		1,650	1.5	09.31	28.31	04.65	14.15

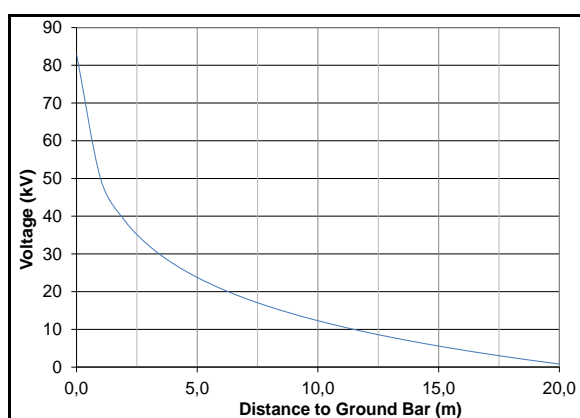
c. Potential difference in ground

The data listed in Tab. 6 to 8 are the results of simulations using the Law of Ohm ($U_{AB} = R_{AB} \cdot I_R$) and equation (8) about electrical resistivity. The calculations have estimated the electrical resistances of the soil in shape of cylindrical layers as shown in Fig. 2. Thus, the values of voltage drop was willing in sequential steps of

1.00 m and starting from the vertical single bar in soil (grounding grid). In addition, the simulation used some different designs by varying the I_R current in the rod, the ρ electrical resistivity of the soil and l length of the ground rod. The graphic in Fig. 3 represents the curve of the electrical voltage drop on the ground according to the parameters of first columns of Tab. 6, to $I_R = 10$ kA, $\rho = 50 \Omega \cdot m$ and $l = 2.40$ m.

Table 6 – Ground Potential Difference for a single bar

Ir (kA)	10	30	10	30	10	30
ρ ($\Omega.m$)	50	50	100	100	100	100
l (m)	2.40	2.40	2.40	2.40	3.00	3.00
Steps (m)	ΔV (kV)					
0.0 – 1.0	33.16	99.47	66.31	198.94	53.05	159.15
1.0 – 2.0	11.05	33.16	22.10	66.31	17.68	53.05
2.0 – 3.0	6.63	19.89	13.26	39.79	10.61	31.83
3.0 – 4.0	4.74	14.21	9.47	28.42	7.58	22.74
4.0 – 5.0	3.68	11.05	7.37	22.10	5.89	17.68
5.0 – 6.0	3.01	9.04	6.03	18.09	4.82	14.47
6.0 – 7.0	2.55	7.65	5.10	15.30	4.08	12.24
7.0 – 8.0	2.21	6.63	4.42	13.26	3.54	10.61
8.0 – 9.0	1.95	5.85	3.90	11.70	3.12	9.36
9.0 – 10.0	1.75	5.24	3.49	10.47	2.79	8.38
10.0 – 11.0	1.58	4.74	3.16	9.47	2.53	7.58
11.0 – 12.0	1.44	4.32	2.88	8.65	2.31	6.92
12.0 – 13.0	1.33	3.98	2.65	7.96	2.12	6.37
13.0 – 14.0	1.23	3.68	2.46	7.37	1.96	5.89
14.0 – 15.0	1.14	3.43	2.29	6.86	1.83	5.49
15.0 – 16.0	1.07	3.21	2.14	6.42	1.71	5.13
16.0 – 17.0	1.00	3.01	2.01	6.03	1.61	4.82
17.0 – 18.0	0.95	2.84	1.89	5.68	1.52	4.55
18.0 – 19.0	0.90	2.69	1.79	5.38	1.43	4.30
19.0 – 20.0	0.85	2.55	1.70	5.10	1.36	4.08

Fig. 3: Voltage drop on ground ($I_R = 10$ kA, $\rho = 50 \Omega.m$ and $l = 2.40$ m).

The difference between any two consecutive points in soil (steps) in Tab. 6 indicates the voltage drop or potential difference between couple of ground points. The distance

refers to the radial lengths starting from earth rod. The voltage drop values listed in Tab. 1 to 6 are the results of the suggested methodology [26] up to a distance of 20.00 m from a ground rod. However, considering the methodology for distance up to 1,000 m using same parameters (I_R , ρ and l), proving the same values for the first 20.00 m as computed in Tab. 6. In addition, confirming the values of voltage drop or pitch voltage varied in direct proportional to the variation of lightning current on the ground bar I_R and the ρ electrical resistivity of the soil and inversely proportional to the variation of the l length of the bar.

d. Potential difference – Case study 1

The diagram in Fig. 4 represents the configuration of the grounding systems (single bars) of a building with lightning protection systems (LPS) and a safety distance s from a rooftop PVS array. The H_1 ground bar represents the grounding of the LPS at 0.0 m milestone, H_2 is the

ground rod to DC/AC converter and photovoltaic array spaced in 10.0 m from H₁. The H₃ bar is grounding system for neutral wire in electrical main board at a distance of 20.0 m from H₁.

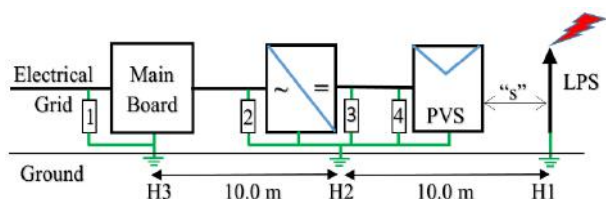


Fig. 4: Diagram for PV system with LPS.

The design of Fig. 4 consists of LPS with isolated grounding or non-equipotentialization among the all three grounding systems (H₁ to H₃). In case of lightning strikes in the LPS, it will rise the potential in H₁ and cause

different potentials in others ground electrodes by voltage drop, according to Tab. 7. The results applied the data from the first column of Tab. 6, considering the spacing of 10.00 m. The analysis of overvoltage has considered the values of potential differences between the three grounding bars with LPS stuck:

- H₁–H₂ = 70.70 kV (LPS to DC/AC converter)
- H₂ – H₃ = 11.50 kV (DC/AC converter to board)
- H₁–H₃ = 82.20 kV (LPS to DC/AC converter)

The potential difference between the three independent grounding systems is due to the lack of equipotentialization. There is no interconnection between H₁, H₂ and H₃ isolated grounding bars to the same reference of grounding system, as recommended in the TN-S ground diagram for electrical system by standards [31,32].

Table 7 – Ground Potential Difference for PVS with LPS

Ir (kA)	10	30	10	30	10	30
ρ (Ω .m)	50	50	100	100	100	100
l (m)	2.40	2.40	2.40	2.40	3.00	3.00
Steps (m)	ΔV (kV)					
00.0 – 10.0	70.70	212.2	141.5	424.4	113.2	339.5
10.0 – 20.0	11.50	34.50	22.90	68.90	18.30	53.10
00.0 – 20.0	82.20	246.7	164.4	493.3	131.5	394.6

The scheme as in Fig. 5 proposed the safety operation of a photovoltaic system in TN-S grounding system with equipotentialization. Otherwise, the interconnection of the ground rods will not guarantee the equipotentialization of the differences of potential. In case, it will only allow the circulation of abnormal current induced in soil during the occurrence of atmospheric discharges.

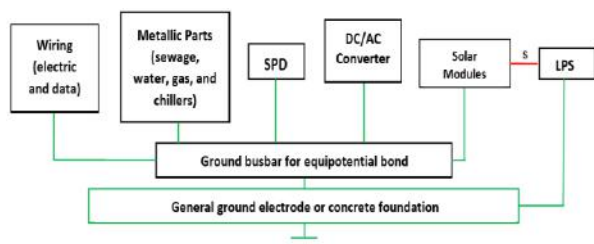


Fig. 5: TN-S grounding and equipotential diagram.

Moreover, if the distance from the solar modules to lightning protection system, as in Fig. 5, is less than the safety distance (sparking) specified by standard's directives, it will be also necessary to provide equipotentialization of structure of solar array and the LPS [33].

e. Potential difference – Case study 2

The diagram as in Fig. 6 represents the configuration of a building without lightning protection system with only two isolated grounding grids and without equipotentialization. The H₂ rod is for the grounding of the DC/AC converter and H₃ rod for grounding of neutral wire from the power system of electricity utility in the main board of the building. The distance between the two ground bars (H₂ to H₃) is 10.0 m. In case of direct lightning strike over array structure of the photovoltaic system, there will be generated a potential difference between the two grounding electrodes.

The values presented in Tab. 8 came from the data listed in the first column of Tab. 6, considering the step of 10.00 m. The analysis of the estimations identified the following potential differences between the two grounding bars (with no LPS):

- H₂ – H₃ = 70.70 kV (DC/AC converter to board)

Thus, the conclusion about the case studies 1 and 2 is that the potential difference composed by H₂ and H₃ grounding systems has increased from 11.50 to 70.70 kV considering the building and PV system with or without

LPS, respectively. In conclusion, the worst situation for DC/AC converter is case 2 or without LPS.

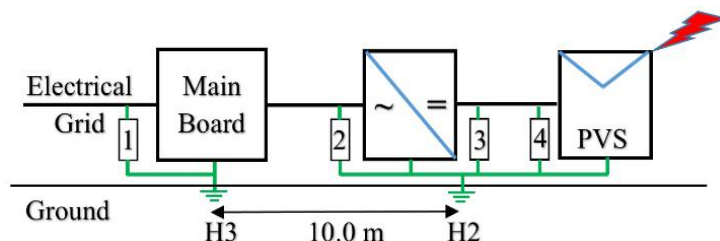


Fig. 6: Diagram for PV system without LPS

Table 8 – Ground Potential Difference for PVS without LPS

Ir (kA)	10	30	10	30	10	30
ρ (Ω .m)	50	50	100	100	100	100
l (m)	2.40	2.40	2.40	2.40	3.00	3.00
Steps (m)	ΔV (kV)					
00.0 – 10.0	70.70	212.2	141.5	424.4	113.2	339.5

In both situations, case 1 (11.50 kV) and case 2 (70.70 kV), the grounding systems submits the connections (T-N) of DC/AC inverter to overvoltage transferred by the two H_2 and H_3 grounding systems, as shown in Fig. 7. It is due to the lack of equipotentialization that can breakdown the converter. Thus, H_2 and H_3 ground rods will submit the SPD₂ to overvoltage as shown in Fig. 4 and 6 during lightning strikes. In both cases, the electrical transient will flow through the neutral conductor in an unconventional direction, causing an inverted polarity over SPD₂. The four impedances connected in series and composed by the neutral wire, SPD₂, H_2 and H_3 ground bars, will divide the intensity of induced overvoltage. In addition, all SPD of the conductor's phases of the AC installation will face the same type of electrical disturbance (electromagnetic impulse). Thus, the methods developed in this paper can be useful to support the analysis of risk management to decide a suitable LPS and SPD before installing a solar PV system.

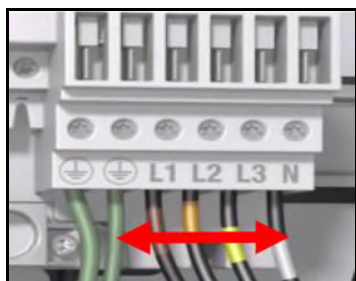


Fig. 7: Potential difference in T N terminals

IV. CONCLUSIONS

This study estimated the effects of lightning strikes on photovoltaic systems. It verified the fundamentals of electromagnetism and Ohm's laws can be an effective support as scientific tool for standards directives to the management of risks and assessment of the effects caused by lightning strikes in photovoltaic microgeneration systems. It researched to proper mathematical models for estimation of induced voltage and current in electrical circuits by lightning struck in PV systems, with and without LPS. The first model applied to simulate inductions in DC circuits of PV systems with LPS, and the second model without LPS. It was verified less induction of voltages and currents in electrical circuits and devices of PV systems operating in structures with LPS than without LPS.

For the simulation, it was considered a PV system of a 2.65 kWp PV System composed by 10 solar modules of 1.65 x 0.99 m, each, as shown in Fig. 1 and considering the lightning protection system with only one down conductor to ground grid. The estimations pointed out peaks up to 201,6 kV and 28,3 kA (200 kA/ μ s impulse rate) induced in DC circuits by lightning strikes, according to type of wiring as leapfrog or daisy chain, distances from LPS and tilt angle. The estimated values of inductions can support the definition of the surge protection device or SPD class for protection of the photovoltaic system, giving reasons to application of a robust class of SPD in buildings without LPS.

The results presented in Tab. 1 to Tab. 5 was compared to similar works (peers) treating the effect of lightning on a

solar photovoltaic system and lightning performance analysis of a rooftop grid-connected solar photovoltaic without external lightning protection system.

The lightning strike or discharge of atmospheric electricity originates potential differences on the ground, causing voltage drops influenced by the current intensity, soil resistivity and grounding system configuration. These are the main cause of induction voltages and abnormal currents in several building installations and PV components (inverters, solar panels, etc.). The results pointed out that up to 70.7 kV overvoltage in the AC terminals of inverter due to design of the grounding systems and caused by lightning. Therefore, the results of the present work listed in Tab. 6 to Tab. 8 are a new type of proposition for evaluating the induced voltages by grounding systems in devices of PV power systems. Therefore, the equipotentialization method completes the protection against the electromagnetic effects of lightning on the ground.

Thus, the methods researched in this paper are propositions for assessment of performance, design improving of LPS projects and verifications of SPD specifications. In addition, as scientific support to the directives of standards for protection of PV system.

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