Energy Syst (2016) 7:469–482
DOI 10.1007/s12667-015-0176-2

ORIGINAL PAPER

Lightning protection of PV systems

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Received: 9 October 2015 / Accepted: 3 November 2015 / Published online: 23 December 2015

Abstract The lightning protection of photovoltaic installations is of great importance, in order to warrant the uninterrupted operation of the system and avoid faults and damages of the equipment. Atmospheric discharges influence the proper operation of the photovoltaic generators and their installation, involving also sensitive electronic equipment. The determination of the need for lightning protection and the evaluation of the performance of a risk management analysis are the first steps, in order to adopt the appropriate protective measures against lightning. Scope of the current work is to summarize the basic lightning protection techniques, taking into consideration the Standards, the international literature and the common practice. The risk management, the external and internal lightning protection system, the selection of the characteristics of the equipment and the grounding system are discussed in the current paper.

Keywords Photovoltaic · Lightning · Surge protective devices · Induced overvoltages · Grounding

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1 Introduction

Photovoltaic (PV) systems, due to their expanded surface and their installation position in wide-open areas, are vulnerable to direct or indirect atmospheric discharges, which can cause damages and failures to the equipment and interruption of their normal operation. The layout of a typical PV installation is larger in comparison with conventional power systems, so the probability to be struck by lightning is higher. PV installation include many wire conductors of small cross section (the input and output cables in the junctions, the metal frame and bracket of the solar modules, the grounding system, the lightning terminals of the buildings, etc.), which are the basic carriers of energy and, simultaneously, the main coupling channels of electromagnetic interference [1].

Despite the fact that PV systems face the risk of damage from lightning, many PV plants are not protected against lightning and the designers ignore or underestimate the need for surge protection [2]. The lack of lightning protection system can cause significant destructions and damages of critical electromechanical parts of the PV installation; note that some times the cost of the damages exceeds the cost of the lightning protection system (LPS) implementation. Moreover, an inadequate protection against lightning phenomena can increase the time of the return of investment of the PV power generating system [3]. Therefore, it is recommended to take into consideration techno-economically balanced protection measures [4]. For these reasons, the design and the establishment of an appropriate LPS is necessary, in order to prevent the development of overvoltages and restrict the repercussions of a potential lightning hit. However, only the avoidance of lightning attachment to unprotected parts of the installation is insufficient, since lightning currents passing through the LPS parts may still impact on the PV system due to inductive coupling. Hence strategic placement of PV systems and shielding of conducting systems wherever possible is recommended [5]. In any case, the compliance with the national and international standards is important, in order the guarantee the effectiveness of the protection measures and consequently to ensure the safe operation of the installation and the quality of the supplied energy [6].

Various researches have studied, either theoretically (by using appropriate simulation tools) [1,2,5,7–10] or experimentally (by performing laboratory or field measurements and tests) [11–17] the lightning performance of PV systems. In [7] the dynamic lightning protection, which focuses on the preventive actions for improving lightning performance of the whole system is discussed. In [1] a sensitivity analysis is performed for the development of lightning overvoltages in a rooftop PV system, taking into consideration the effect of lightning striking spot, the lightning current amplitude, the building height, the soil resistivity and the distance between the solar arrays and the external protection system. In [2] an appropriate computer program has been developed for making a decision on either the need to install lightning protection in PV system or not; the computer program can give a design on how to install lightning rods by using the protective angle method. In [8] two different external LPS installed to two different PV technology power plant systems are compared. The respective system performances were compared in terms of total energy generated and energy yield. The authors emphasize the importance for power plants to minimize PV system lightning damages by installing LPS and highlight the role of the shadow of lightning poles that drops on the PV modules to increase solar cell temperature and reduce power generation. The researchers in [9] estimate the arising overvoltages due to lightning discharges and evaluate the actual need of lightning protection measures on the basis of the results of the risk analysis and of the protection costs. In [5] the impact of lightning on PV systems is directly related to the isokeraunic level of the region and elevation of the building, providing also recommendations for the appropriate design of the air termination system for a roof with PV panels in high isokeraunic regions. In [10] the authors implement the generalized modified mesh current method, in order to establish a time-domain multiport model of thin-wire system for lightning transient simulation for PV power system with and without external LPS. In [11] the researchers present the experiences during the measurements of the effects of lightning transient currents injected by means of a surge generator on the DC overvoltage protection system on a real MW-Class PV plant. In [17] the voltage at the terminals of two PV arrays is monitored, considering lightning-induced voltage transients in PV arrays. In [12] scaled laboratory tests and geometrically accurate simulation models are presented in an attempt to assess the induced overvoltages on long DC cabling loops. In [13] the effect of lightning impulse voltages on the power output of the PV module is studied. In [14], experiments of applying standard lightning impulse voltages on a type of polycrystalline silicon PV module were performed and comparisons of their dark I-V characteristics curves and I–V characteristics are presented. In [15] a lightning surge analysis model with a concrete foundation for PV panels was made and has experimentally validated. The foundation model was used to model a DC power distribution system within a full-scale PV system, and the required current withstand capability of surge protective devices (SPDs) is evaluated using the finite difference time domain (FDTD) method. The PV panel damage caused during a lightning strike was discussed in [16].

The current work deals with the design of a protection system for PV installations against lightning. It emphasizes to the coordination of the various surge protection parts and summarizes the basic procedures for the sufficient and effective study of PV lightning performance. The presented design techniques include the risk management, the separation into lightning protection zones (LPZ), the internal and external LPS, the selection of the electrical characteristics, the efficient placement of the surge protective devices (SPDs) and the grounding system, according to the existing Standards, considering, simultaneously, the international research results and the common practice.

2 Overvoltages in PV installation

PV systems have a major role in the renewable energy technologies, since they are eco-friendly, nonpolluting and reliable power sources [18–21]. The application of PV technology concern both stand-alone and grid-connected systems [18,22]. Lightning is a main cause of faults, damages and interruptions in any kind of PV systems. Direct and indirect lightning flashes can damage PV modules and equipment (inverters, cables, batteries [22], boards, etc.). Direct lightning hits at the basic elements of the PV or at the external lightning protection system (LPS) resulting to the insulation breakdown and the grounding potential rise. In addition, lightning strikes create a magnetic field around the flash channel or/and the conductors, inducing surges in all wiring loops of the installation [19].

The scale of the consequences depends on:

- the characteristics of the structure,
- the LPS,
- the characteristics of the lightning flash, and,
- the lightning position hit.

According to [23] the sources of the expected damages due to lightning currents are distinguished as following: flashes to the PV ($S1$), flashes near the PV ($S2$), flashes to a service which is connected to the PV ($S3$) and flashes near a service which is connected to the PV ($S4$). As result, the developed overvoltages can cause three basic types of damages, i.e., injury of the occupants due to touch and step voltages ($D1$), physical damages ($D2$) and failures of electrical and electronic system due to lightning electromagnetic impulse (LEMP) ($D3$) [23]. Each type of the above damages, alone or in combination with others, may produce different consequential losses, i.e., loss of human life ($L1$), loss of service to the public ($L2$), loss of cultural heritage ($L3$) and loss of economic value ($L4$) [23,24].

3 Risk management

The necessity a PV lightning protection system shall be examined, in an effort to reduce the pre-mentioned losses ($L1$, $L2$, $L3$, $L4$). The determination of the need for lightning protection and the design of the lightning protection system is performed according to the risk management procedure, described in [3,24]. The risk R is the value of a probable average annual loss. For each type of loss ($L1 - L4$) corresponds a type of risk, i.e., risk of loss of human life ($R1$), risk of loss of service to the public ($R2$), risk of cultural heritage ($R3$) and risk of loss of economic value ($R4$). Each risk is the sum of different risk components R_X (where $X = A, B, C, M, U, V, W, Z$), which are grouped according to the source and the type of the damage [24]. Each risk component R_A, R_B, R_C, R_M, R_U, R_V, R_W and R_Z is calculated according to the equation:

$$R_X = N_X \cdot P_X \cdot L_X \qquad (1)$$

where:

N_X is the number of dangerous events per annum,

P_X is the probability of damage to the structure, and

L_X is the consequent loss.

N_X depends on the ground flash density and the equivalent collection area of the object, taking into account correction factors for objects' physical characteristics. P_X is selected by a Table presented in [24], considering various cases. L_X depends on the number of persons and the time for which they remain in the hazardous place, the type and importance of the service provided to the public and the value of the goods affected by the damage [19,24].

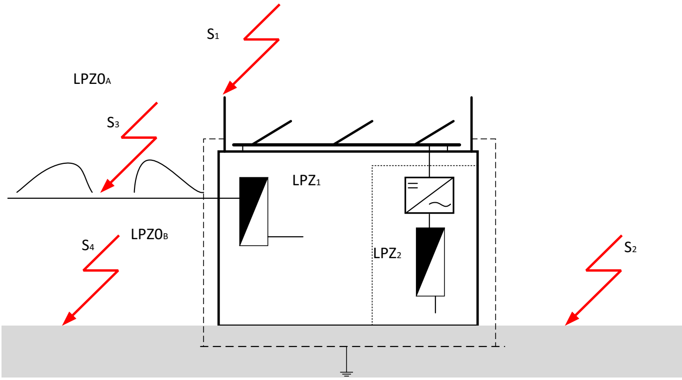


Fig. 1 Lightning protection zones for a residential PV installation

Figure 1 presents the lightning protection zones (LPZ) in a residential PV; protection measures such as LPS, magnetic shielding and surge protective devices (SPDs) determine the above zones. $LPZ0_A$ is threated by the direct lightning strike and the full electromagnetic filed, while $LPZ0_B$ is protected against direct hit and is at risk only by the non-attenuated electric field. In $LPZ_{1,2,\ldots n}$ the surge currents are limited due to sharing and SPDs' installation; in addition, spatial shielding may attenuate the lightning electromagnetic field [24].

4 External and internal lightning protection system

Risk management analysis determines the need of protection of the PV installation. In case that lightning protection is required, the appropriate lightning protection level (LPL) has to be defined, according to [24,25]. These LPLs equate directly to classes of LPS [23]. IEC 62305-1 has defined four LPLs, based on probable minimum and maximum lightning current parameters, i.e., peak current (kA), short stroke charge (C), specific energy (MJ/Ω) and steepness (kA/μs). The maximum values are used to design lightning protection components, since the minimum values are used for the position of the air termination system.

The LPS comprises external and internal parts; the external LPS is intended to intercept direct lightning flashes to the PV installation and to disperse the lightning currents into the earth without causing thermal or mechanical damage, nor dangerous sparking which may cause fire or explosion [25,26]. The external LPS is composed of the air termination system, the down conductor system and the earth termination system. The protection angle, the rolling sphere and the mesh method are common practices for the design of the external LPS in a way that all PV equipment to be included to the protection volume. The classification of the LPS, the isolation or not of the air termination system, the use of natural components (attics, guttering, railings, cladding) [27] and the specifications of the grounding system are analytically discussed in [25].

The main scope of the internal LPS is to avoid the occurrence of dangerous sparking within the PV system to be protected, due to lightning current flowing in the external LPS or in other conductive parts. Internal LPS includes equipotential bonding (interconnection of the LPS with structural metal parts, metal installations, internal system, external conductive parts and lines connected to the structure) and electrical insulation between the parts (compliance with a separation distance between the air termination or the down-conductor and the metallic parts of the installation, which is depended on the class of the LPS, the length of the conductors, the insulation material and the sharing of the lightning current) [1,2,28,29].

The described LPS does not warrant the protection of the electrical and electronic equipment of a PV installation against conducted or induced surges, developed by the LEMP. For this reason, the division of the installation to be protected into LPZ is performed, in a way that, for each zone, the LEMP severity is compatible with insulation withstand capability of the equipment. A LEMP protection measures system (LPMS) includes earthing, bonding, magnetic shielding, line routing and coordinated SPD protection. In details the grounding system (Type A or Type B) leads the lightning current to earth; in case of two internal systems, which are referenced to separate grounding systems, the following methods have to be applied, in order to limit the potential difference: (a) several parallel bonding conductors running in the same paths as the electrical cables, or the cables enclosed in grid-like reinforced concrete ducts (or continuously bonded metal conduit), which have been integrated into both of the earth-termination systems; (b) shielded cables with shields of adequate cross-section, and bonded to the separate earthing systems at either end [19,27,30].

An equipotential bonding network reduces the hazardous potential drops between all equipment in the inner LPZ, as well as restricts the magnetic field. The achievement of low impedance bonding system is realized by a meshed bonding network (considering as a 3-d meshed structure), which integrates all metal components aided by equipotential bonding conductors inside the LPZ of the structure (all metal installations, reinforcements in the concrete, gratings, cable ducts, metal flour, supply lines, etc.) directly or through surge protection devices (SPDs). Magnetic shielding (spatial shielding or shielding of internal lines) attenuates the magnetic field and minimizes internal induced overvoltages. Suitable routing of the internal lines minimizes induction loops and reduces internal surges. Spatial shielding and line routing can be combined of used separately.

SPDs are installed between phase and earth in order to protect the electrical and electronic equipment against overvoltages; SPDs present a non-linear voltage-current characteristic, behaving as insulators for nominal current and as conductors in cases of incoming surges. SPDs direct the lightning current to the grounding system through low impedance paths and, simultaneously, keep the developed overvoltages below the insulation withstand of the equipment [31,32].

The designer of the lightning protection system may choose either air termination and down conductor system attached with the PV or air termination and down conductor system non-attached from the PV, in combination with SPDs. It is noted here that the frames of PVs are grounded to the metallic structure (there is electrical continuity between PVs frame and metallic structure). A non-attached lightning protection system consists of a mast, installed away from the PV at a distance greater than [25]:

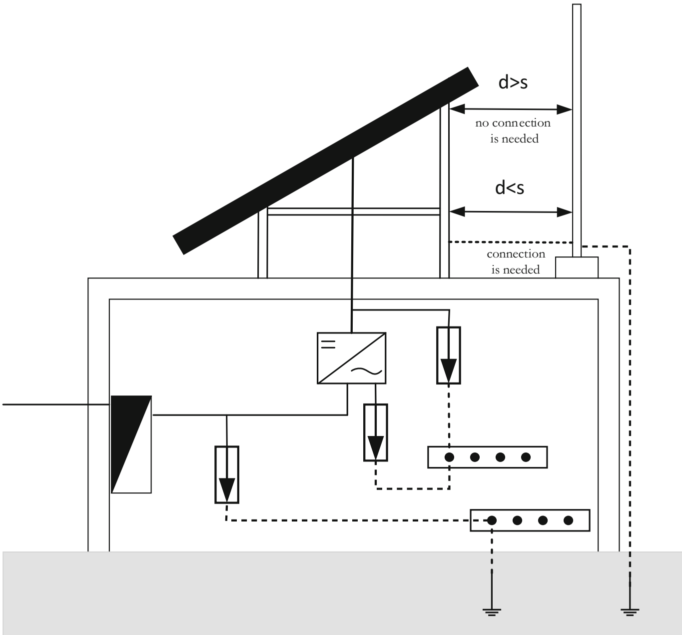


Fig. 2 Attached or non-attached external LPS in combination with SPDs

$$s = \frac{k_i}{k_m} \cdot k_c \cdot l \tag{2}$$

where:

k_i is a constant that depends on the selected class of the lightning protection system,

k_m is a constant that depends on the insulation, and

k_c is a constant that depends on the lightning current flowing in the air termination and the down conductor

l is the length, in m, along the air-termination or the down-conductor, from the point where the separation distance is to be considered, to the nearest equipotential bonding point.

In case that a PV installation is protected against lightning discharges by an external LPS, the above distance s between the PV equipment and the parts of the LPS should be respected, in order to avoid sharing of discharge currents through the metallic components of the PV system. However, in some cases (i.e., PV installed on rooftops) the demanded separation distance s cannot be satisfied, because of lack of adequate space. For this reason, the frames of PVs are connected with LPS, something that affects the selection of the SPDs characteristics [32,33] (Fig. 2).

5 Earthing system

The achievement of low values of grounding resistance in PV installation is of great importance, in order to minimize any potentially dangerous overvoltages. In general, a low earthing resistance (if possible lower than 10 Ω when measured at low frequency) is recommended [25].

The lightning current that hits the PV installation is diverted through down conductors (and SPDs) to the grounding system. According to [25] two basic types of earth electrode arrangements apply, i.e., type A and B arrangements. Type A arrangement comprises horizontal or vertical earth electrodes installed outside the structure to be protected connected to each down-conductor, since Type B arrangement comprises either a ring conductor external to the structure to be protected, in contact with the soil for at least 80 % of its total length, or a foundation earth electrode.

In details, in case of Type A grounding system, the total number of earth electrodes shall be not less than two [25]. Furthermore, in Type B systems with ring conductor, when the radius of the ring electrode is less than the length specified in the Type A system, additional horizontal or vertical electrodes shall be added [32,34].

In [25] details about the configurations, the components the materials and the construction of the earth-termination systems are given. In any case the cost, the lifetime and the galvanic corrosion between metals of dissimilar nature are parameters that should be taken into consideration during the design and the installation of a grounding system [30,34].

6 SPDs: electrical characteristics and installation position

The basic electrical characteristics of SPDs are [35–38]:

Maximum continuous voltage (U_c): it is the rms value of the maximum voltage which may be applied to the terminals of the surge protective device. The value of U_c shall be selected in accordance with the nominal voltage of the system to be protected.

Lightning impulse current (I_{imp}): it is a 10/350 μs impulse current waveform that simulates lightning surges. SPDs must be able to discharge such lightning impulse currents several times without consequential damage to the equipment.

Nominal discharge current (I_n)**:** The nominal discharge current I_n is the peak value of the 8/20 μs impulse current flowing through the SPD.

Voltage protection level (U_p)**:** it denotes the maximum instantaneous value of the voltage on the terminals of an SPD while at the same time characterizes their capacity to limit surges to a residual level.

Short-circuit withstand capability: it is the value of the prospective power-frequency short circuit current controlled by the surge protective device in case it is furnished with an upstream backup fuse (backup protection).

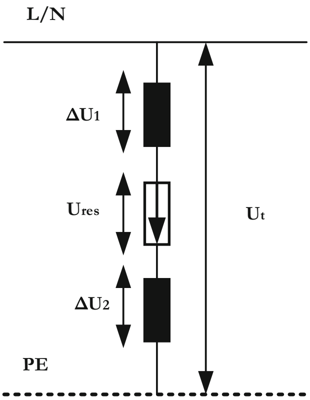
The limiting voltage on the equipment terminals (Fig. 3) is given by the equation:

$$U_t = U_{res} + \Delta U_1 + \Delta U_2 \tag{3}$$

where:

U_t is the limiting voltage on the terminal equipment,
ΔU_1 is the inductive voltage drop on the phase side connection of the SPD, and
ΔU_2 is the inductive voltage drop at the earth-side connection of the SPD.

Fig. 3 Limiting voltage on the terminal equipment



The inductive voltage drop depends on, the resistive (R) and inductive (L) component of the connecting conductors, the impulse injected current (i) and the rate of current change (*di/dt*), according to Eq. (4):

$$\Delta U = R \cdot i + L \cdot \frac{di}{dt} \tag{4}$$

In order to keep this dynamic voltage drop low, the electrician carrying out the work must keep the inductance of the connecting cable and hence its length as low as possible. The installation of SPDs shall be performed with short connection wires, since large loops especially by the PE conductor shall be avoided; they must be installed as close to the terminals of the equipment, by using the shortest and straightest routed conductors of sufficient cross sectional area. In case that the above criterion is not fulfilled, then the developed surges will exceed the insulation level of the equipment to be protected [27,35,39,40].

Surge protection devices (SPD) are divided into three classes [37,41]:

Type I: SPDs type I are installed mainly at the entry point of the installation at the borders between LPZ 0–LPZ 1 or LPZ 0–LPZ 1 and provide primary protection against 10/350 µs lightning current.

Type II: SPDs type II are installed at main node points of the installation at the borders between LPZ 1–LPZ 2 and provide protection against 8/20 µs surge currents.

Type III: SPDs type III provide fine protection against 8/20 µs surge currents and 1.2/50 µs surge overvoltages and they protect sensitive electronic devices from impact by lightning striking far away. Type III SPDs should always be installed at least after at least type II SPDs.

SPDs are connected at critical positions (to both the AC and DC side) of the PV installation and offer primary or secondary protection against overvoltages to the equipment of the system; the appropriate placement of SPDs restricts the developed surges that would otherwise stress the equipment terminals. Furthermore, the effective protection of the PV equipment has to be ensured against oscillation and induction phenomena, which can lead to equipment failures and damages. As far the oscillation phenomena concerns, if the length of the circuit between the SPD and the equipment

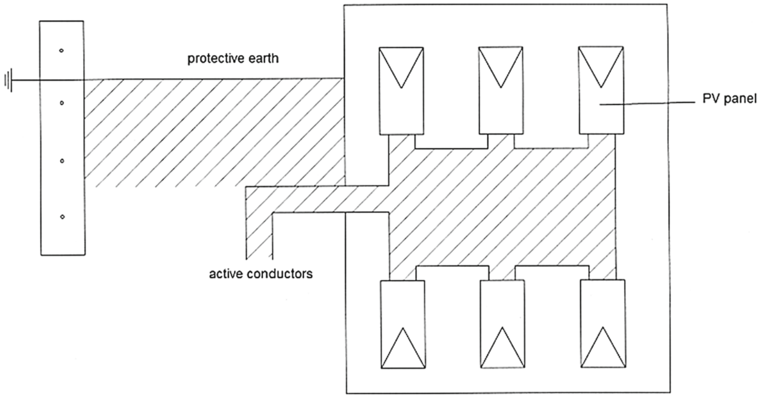


Fig. 4 Induction loops formed in a PV installation

is too long, propagation of surges can lead to overvoltages up to $2U_t$ (in case of an open-circuit at the equipment's terminals); if $U_t > U_w$ (where U_w is the impulse withstand voltage of the equipment) then a fault occurs [19,37].

The oscillation protection distance l_{po} is the maximum length of the circuit between the SPD and the equipment, for which the SPD protection is still adequate. If the circuit length is less than 10 m or $U_t < U_w / 2$, the protection distance l_{po} may be disregarded. When the maximum length of the circuit between the SPD and the equipment is greater than 10 m and $U_t > U_w / 2$, the oscillation protection distance can be estimated using the following equation, taking into account a factor k equal to 25 V/m [19,37]:

$$l_{po} = \frac{U_w - U_t}{k} \quad (5)$$

Lightning flashes can induce an overvoltage in the circuit loop between the SPD and the equipment, downgrading the protection efficiency of the SPD. The induced surges depend on the magnetic field (due to the lightning discharge current) around the flash channel and the down conductors of the LPS, the lightning characteristics, the geometrical characteristics of the PV system and the position of the stroke hit (Fig. 4).

The magnitude of the developed surges depends on the lightning characteristics, the geometrical characteristics of the PV system and the position of the stroke hit. In details, the steepness of the lightning current determines the level of the induced overvoltage, since the induced voltages are proportional to the self-inductance of the loop multiplied by the steepness of the lightning current [19,37]. Induced overvoltages increase also with the dimensions of the loop (i.e., line routing, length of circuit, distance between protective earth conductors and active wires) and decrease with attenuation of the magnetic field strength [41,42]. Approximated equations for the calculation of induced voltages and currents are given for different types of LPS and lightning flashes in [9,19]. The induced overvoltages can also be estimated by appropriate techniques given in [10,17,43–45]. As far as the hit position is concerned, the severity of the overvoltage is inversely proportional to the distance of the point of impact [46–48]. Figure 5 presents the induced overvoltage in relation to the lightning hit position, considering a loop of 1 m^2.

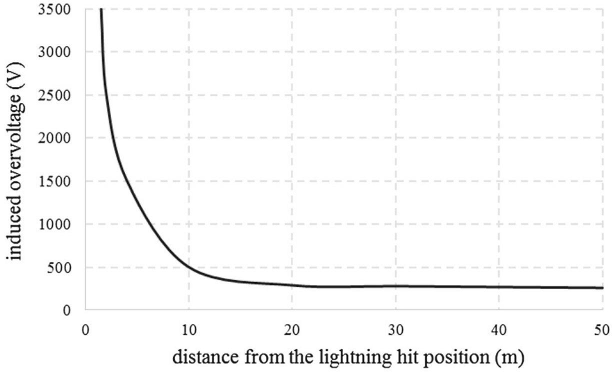
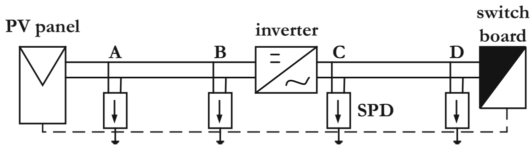


Fig. 5 Developed induced overvoltage in function with the lightning hit position (loop surface: 1 m^2) [49]

Fig. 6 SPDs installation positions



The induction protection distance l_{pi} is the maximum length of the circuit between the SPD and the equipment, for which the protection of the SPD is still adequate. The avoidance of large loop surfaces or line shielding car reduce the effect of induced phenomena, so the induction protection distance l_{pi} can be disregarded. Otherwise, the induction protection distance l_{pi} can be estimated using the following equation:

$$l_{pi} = \frac{U_w - U_t}{3000 \cdot K_{S1} \cdot K_{S2} \cdot K_{S3}} \tag{6}$$

where:

K_{S1} is the factor of the shielding effectiveness at boundary LPZ 0/1,

K_{S2} is the factor of the shielding effectiveness at boundary LPZ 1/2 or higher, and

K_{S3} is the factor of routing precaution on wiring [19,37].

Figure 6 presents a simplified PV system and the installation positions of the SPDs (A, B, C, D). SPDs at A protect the PV panels against atmospheric discharges; their implementation is not obligatory in case that the length between A and B is not greater than 10 m. SPDs at positions B and D protect the DC side of the inverter and the entrance of the main switching board, correspondingly, and are always required. Note that, the developed overvoltages on DC wiring are also influenced by the grounding system, the set-up conditions of each PV system and the wirings [50]. SPDs at C protect the AC side of the inverter and are required if the distance between C and D exceeds 10 m [36].

As far as concerning the selection of the type (class) of the SPDs, Table 1 summarizes the basic cases, considering the external LPS and the separation distance s (see Eq. (2)) [30].

Table 1 Basic cases of SPDs types

Lighting protection	DC side of inverter	AC side of inverter
No external LPS	SPD type II	SPD Type II
External LPS: d >**s**	SPD type II	SPD Type I
External LPS: d <**s**	SPD Type I	SPD type I

7 Conclusions

The current paper provides an overview of the basic aspects about the lighting protection of PV installations. The initial estimation of the possible dangers due to atmospheric surges and the need for protection against lightning strikes (considering techno-economic criteria) is the first step for the efficient design of LPS. The compliance with Standards requirements (e.g., separation distances, grounding systems, etc.) and the suitable selection and installation of SPDs, ensures the adequate lightning protection, achieving a longer operational PV life by reducing the possibility of faults and interruptions.

Acknowledgments The paper is supported by IKY fellowships of excellence for postgraduate studies in Greece - Siemens program.

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