A REVIEW OF RESEARCH ON LIGHTNING PROTECTION FOR PHOTOVOLTAIC SYSTEMS

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Abstract: The global PV market has grown extensively for small- to large-scale systems. Inevitably, this leads to the increased development of PV technology. PV systems are intrinsically exposed to weather phenomena. One such phenomenon is lightning. Direct and indirect effects of lightning can cause damage to PV systems. However, lightning protection for PV systems is often neglected and existing standards for protection are underdeveloped. In this paper, previous work is analysed to understand the interaction between lightning and PV systems and to ascertain gaps in current knowledge thereof. Investigation of these aspects will ultimately assist in understanding lightning risk, protection system design and aid in the development of lightning protection standards for PV in the renewable energy industry.

Key words: Lightning protection, photovoltaic systems, risk assessment, lightning protection system.

1. INTRODUCTION

The emergence of photovoltaic (PV) technology as one of the major contributors of renewable energy production is reflected by the global installed capacity of 303 GW at the end of 2016 [1]. This represents a significant growth from 227 GW in 2015 [2]. The proliferation of solar PV prompts a focus on the enhancement of accompanying system technologies. One such technological aspect is protection. PV system protection is required due to electrical faults and natural occurrences such as lightning. PV systems can be damaged by direct or indirect lightning resulting in electrical surges or fire, causing harm to persons and property [3]. Lightning could have distinct effects on PV components based on the system configuration. Moreover, there will be an effect on the risk assessment and protection requirements. This paper is a review on lightning protection for PV systems where risk assessment considerations for lightning protection system (LPS) design requirements are assessed and recommendations for future work are given. This is based on previous work done of which there is currently a significant lack of.

2. BACKGROUND

In recent times, there has been a steady increase in PV market penetration. This includes residential, medium to large commercial applications, and grid-connected PV plant installations. The relatively modern status of PV technology and its associated widespread use warrants careful consideration of its requirements for stable operation. There have been advancements in PV module and inverter efficiencies, energy storage and installation methods due to increased competition in the PV market. PV standards are underdeveloped which, along with the rising number of independent PV system installers, increases the risk factor of these installations. Lightning risk is one of the factors that is often overlooked. Lightning strikes are commonplace worldwide with some areas experiencing higher ground flash densities than others [4]. Hence the importance of considering this phenomenon in relation to the protection of any type of electrical equipment, system or physical structure. The IEC 62305 standards on lightning protection [5–8] have been developed for lightning protection requirements based on existing structures, environmental and system conditions. However, they do not contain specific guidelines for lightning protection of PV installations. Inherently, PV modules are prone to exposure to the elements due to factors such as:

- Requirement of unobstructed exposure to the sun - hence no physical shielding
- Rooftop location for smaller systems - hence risk of a direct lightning strike; and
- Higher lightning ground flash density over an area attributing to field dimensions for large-scale PV plants.

Lightning protection of PV systems should be viewed holistically for systematic evaluation and design. Each system behaves differently based on site-specific conditions. Hence, a comprehensive risk assessment should be carried out before designing an appropriate LPS. It should be highlighted that there is a notable lack of research on the interaction between lightning and PV systems. The factors influencing risk assessment and LPS requirements with regards to PV based on existing research are analysed in this paper.

3. LIGHTNING RISK ASSESSMENT

A risk assessment for a structure should be carried out according to IEC 62305-2 [6]. This standard serves the purpose of calculating the risk of lightning damage. If $R > R_T$, where R is the calculated risk and R_T is the threshold risk, an LPS for protection of the structure will be required to manage the risk. There are no adaptations of the IEC risk assessment standard specifically for PV systems. The work done on risk assessment in [9–14] is based on field experience and interpretations of the existing standard. There are a number of equations used in the risk assessment process [6]. The base equation used to calculate the value of each risk component is:

$$R_X = N_X \times P_X \times L_X \tag{1}$$

where R_X is the risk component, N_X is the number of dangerous events per annum (geographically based), P_X is the probability of damage and L_X is the consequential loss. The details of the above-mentioned constituents can be found in [6]. Using (1), a number of risk components are calculated and used to evaluate the total risk for losses applicable to the system as indicated in Table 1. Each

Table 1: Pertinent risks related to a structure

Designation	Risk
R_1	Loss of human life
R_2	Loss of service to the public
R_3	Loss of cultural heritage
R_4	Loss of economic value

risk in Table 1 consists of risk components which are defined for the specific scenario. In the risk assessment work for PV structures followed in [9] and [10], only R_1 and R_4 are considered, whereas [12] only considers the latter. These considerations are for large commercial to plant size applications. It would be expected that for a grid connected plant, R_2, would be considered. This would be of more consequence if the PV plant were used as the primary source of electricity generation. In terms of independent installations, residential sized systems are often disregarded. There could possibly be a high risk of loss of human life due to the proximity of the PV structure to the household. Consequential effects of lightning such as step potential, touch potential and side flashes should be considered as part of the risk. In terms of economic loss, the risk is calculated again using (1). In addition, the cost of total loss may be calculated using (2) as found in [6]:

$$c_L = \sum c_{LZ} = R_4 \times c_t \tag{2}$$

where c_L is the cost of total loss, c_{LZ} is the cost of loss in a zone, R_4 is the risk of loss of economic value and c_t is the total value of the structure.

In [9], new factors for the calculation of total economic loss such as the damage factor and revenue loss have been added to the calculation in (2). Thus, the cost benefits or losses of the installation of lightning protection for the PV system can be quantified. The cost calculation is done zonally. This process is followed for all other risk evaluations (R_1 to R_4) as stipulated in IEC 62305-2. Zonal risk assessment allows for modular calculation of risks and aids in the design of a cost effective LPS. The factors to consider for zonal risk assessment are the lightning point of strike and the electromagnetic effects in different locations of the structure [6]. Figure 1, adapted from [12], summarizes the considerations for zonal risk assessment of a rooftop PV system. The structure is divided into zones

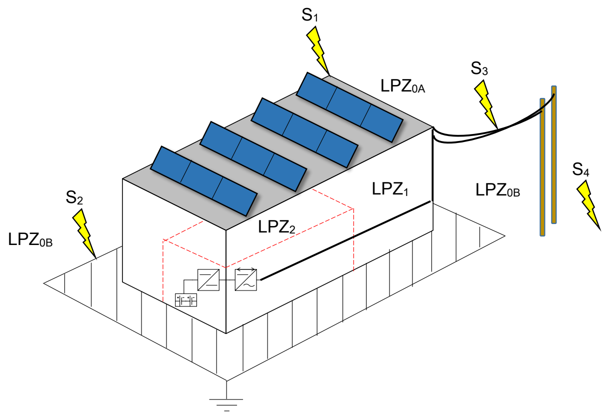

Figure 1: Lightning protection zones based on point of strike

according to the different types of protection required. The external LPS does not fully protect the electrical system inside the structure. Hence, surge protective devices are required for protection against LEMP [12] based on the required lightning protection level (LPL), protection zone and class of protection detailed in IEC 62305-4 [8]. This refers to the internal protection. Based on Figure 1, the data illustrated is summarised in Table 2 for the point of strike and Table 3 for the proposed lightning protection zones (LPZ). Lightning strikes at

Table 2: Lightning point of strike for structure

Point of strike	
S_1	Direct to structure
S_2	Near structure
S_3	Direct to line
S_4	Near line

Table 3: Lightning protection zones for PV system

Lightning protection zone (LPZ)	
LPZ_{0A}	Direct lightning
LPZ_{0B}	Non-direct lightning, unattenuated EMP
$LPZ_{1,2}$	Attenuated EMP, limited surge current

different locations will have different effects on the PV system in the protection zones. This will in turn have an effect on the risk assessment. All factors related to the risk assessment of a PV structure should follow the zonal approach where specifics related to PV should be included.

A case study of a 250 kWp rooftop PV system presented in [10] determines the expected risk assessment variations of the standard specifically for grid-connected PV. It is assumed that there are no pre-installed lightning protection systems and that all components (other than the PV modules) are inside the structure. The risk assessment process followed in [10] is illustrated in Figure 2. Figure 2 represents an amendment of the IEC 62305-2

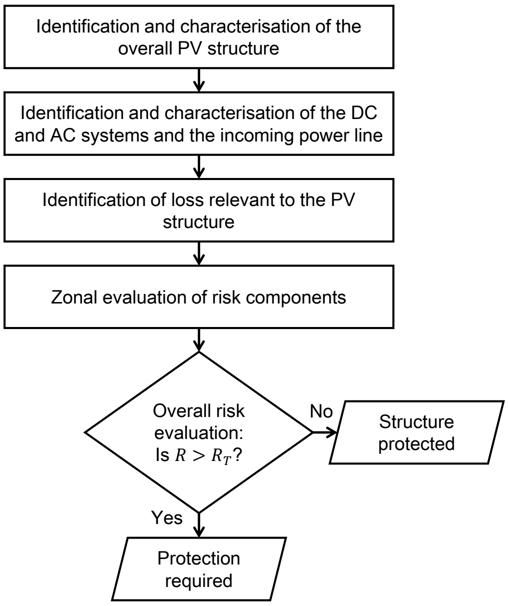

Figure 2: Risk assessment process for case study

risk assessment process. The characterisation of the overall PV structure looks at the physical attributes of the structure. This includes the dimensions of the PV array, location, shielding of the panels and physical protection measures such as fencing. The characteristics of the DC and AC systems and the incoming power line include length and type of cabling, soil resistivity, transformer location, environmental factors, shielding and equipment ratings. All characteristics are assigned a numerical value pertaining to the risk using the standard as a guide. Thereafter, losses in the structure are identified in relation to the risk factor.

For zonal evaluation of risks, R_1 and R_4 are considered. The zones evaluated with respect to these risks are the rooftop and the inside of the structure. R_1 includes factors such as soil surface, shock protection and loss for the rooftop and risk of fire, probability of damage and floor surface for the inside of the structure. R_4 includes similar factors. For the overall risk evaluation, R_1 (including R_2 and R_3 in other cases) directly affects the requirements of the LPS with respect to the threshold risk. R_4 is only considered for the cost effectiveness of the protection. It may be beneficial to not only perform a quantitative assessment of risk as outlined in the standard but also to include a qualitative assessment to take into account unique risks in the specific environment. This would include social aspects that are site specific such as overall awareness of damaging lightning effects and its effect on the risk assessment in the vicinity of the structure.

There are many factors of risk assessment to consider which are not described by a specific standard. There is room for development in terms of international standards specific to PV. For instance, in Germany, supplements to the IEC 62305-2 standard already exist specifically for lightning protection of PV systems [15]. This would be especially beneficial for risk assessment where it is often a speculative process. The complexity lies in incorporating the PV system into the risk assessment process for different scenarios. Often, cost is one of the main concerns when implementing lightning protection. It was found in [14] that for a particular 200 kWp PV system, lightning protection accounted for an extra 3.6% of the total cost of the PV system. This is a relatively low added cost. An optimal LPS assists in managing calculated risk. Different PV topologies will require different approaches. The unique characteristics of PV system components will influence the risk assessment and continuous investigation of the effects of lightning on these components will supplement the development of the risk assessment process.

4. LIGHTNING PROTECTION SYSTEM

Previous work has been done on some of the effects that lightning has on a PV system and hence the requirements of the LPS. Both the external and internal LPS are considered where direct and indirect strikes may have consequential effects on PV equipment. Figure 3 is a rudimentary block layout of a PV system indicating the probable external and internal LPS requirements. In most

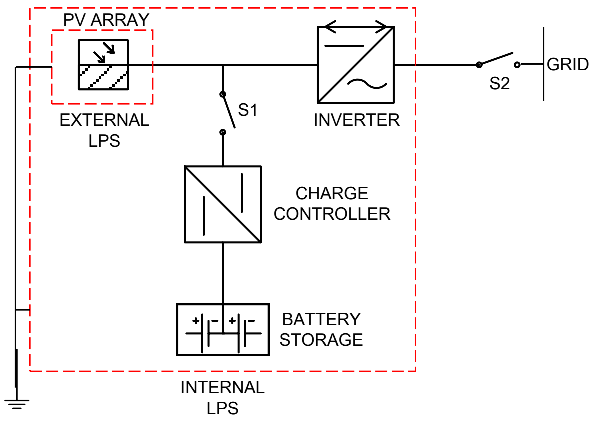

Figure 3: External and internal LPS for PV components

cases, the PV array is the only equipment exposed to direct lightning. However, both the panels and the power electronics will experience surges, hence the need for the internal LPS. The external LPS does however play a role in minimising surges to all parts of the system. Variations in lightning protection requirements may exist based on the system being grid-connected or off-grid as well as small-scale rooftop or free-field plant size. Design of the LPS is based on the lightning protection standards. However, these standards cannot be used in isolation. For example, standards for material selection requirements for external LPS design can be found in the IEC 62561 standards. Also, SPD requirements for internal LPS design can be found in the IEC 61643 standards. These standards should be used in conjunction with standards [5–8] for comprehensive design and implementation of an LPS. Research on the interaction between lightning and PV system components is ongoing. The work done thus far is outlined in the following sections.

4.1 Direct lightning strike

Previous experimental and simulation work has been done on some aspects of external protection of a PV system from a direct lightning strike. The components under consideration based on [5, 7] and previous research is indicated in Table 4. The design of the external LPS follows a top-down approach. Following the risk assessment of the site, a lightning protection level (LPL) is determined which directly correlates to the class of LPS required. This is based on the predetermined lightning current parameters. One of the dependencies of the class of LPS is the design of the air-termination using either the rolling sphere, protection angle or mesh methods [5]. These methods can be applied for rooftop or free-field PV systems where particularly in rooftop applications, due to height, consolidation of the air-termination system is important. In [16], the rolling sphere and protection angle methods are used to determine the positions of the air terminations and the LPZ of the PV array. The protection angle method is used to determine the separation distance of the air termination to the panels so that no flashover occurs due to a direct lightning strike. The separation distance is calculated using (3).

Table 4: Components of an external LPS for PV systems

External Lightning Protection System
Air termination - rolling sphere, protection angle, mesh method
Down conductor - isolated or non-isolated
Earth termination - ground rod material properties
Earth properties - soil resistivity and ionisation, type of foundation
Separation distances - flashover

$$s = \frac{k_i}{k_m}.k_c.l \tag{3}$$

where s is the required separation distance, k_i is a constant dependent on the class of LPS, k_m is a constant dependent on insulation, k_c is a constant dependent on lightning current through the air termination and down conductor, and l is the length from point of separation distance to the nearest equipotential bonding bar [12]. This is important to consider so that no arcing occurs between the air termination and the PV array. The following are considerations for each of the air-termination location methods applicable to PV systems:

- The mesh method is only appropriately used for planar surfaces possibly for inclined roofs with flush mounted panels;
- the protection angle method needs to take into account the shading on the modules due to possible hotspot formation; and,
- the rolling sphere method may not particularly designate the LPZ correctly due to the tilted arrangement of the PV array on flat roofs or ground-mounted systems.

Down conductors are then installed for each air termination. There are two types of air-termination/down conductor interconnections; isolated or non-isolated. Isolated connections are only required when there are flammable substances in the structure [7]. There are investigations done in [17] and [18] on the effects of isolated and non-isolated configurations on the induced overvoltages in cabling loops which forms part of the internal LPS considerations.

The down conductor is connected to earth. The earth termination and earth properties are important for dissipating the high lightning impulse current from a direct strike into ground. In residential PV installations, there is typically no quantitative assessment of the soil properties and the characteristics of the earth termination. Work has been done on these aspects in [19–21] for different PV applications (including residential), where material properties of earth terminations, soil resistivity, soil ionisation and modelling of grounding systems are investigated. It was found in [19] for a rooftop PV installation that a higher resistivity of soil, increases the induced overvoltage in the external LPS which creates a higher ground potential. This is an expected result which is corroborated by the findings in [20] also for a rooftop installation of residential scale.

The ionisation of the soil also plays a role in the induced overvoltage. The greater the soil ionisation, the lower the induced overvoltage as determined in [21] where a 150 kWp system was investigated. This is due to the higher conductivity of the soil where it could safely be assumed the same applies for a small-scale installation. The precise design of an external LPS to conduct current safely and direct it to ground is reliant on accurate dimensioning, material selection and site-specific evaluation. Protection against direct strikes forms one part of the complete LPS where the structure and persons are protected against primary lightning activity. For protection of electrical and electronic equipment against LEMP, an internal LPS is required.

4.2 *Lightning electromagnetic impulse*

The internal LPS is required to protect against surges induced by LEMP in the system. The components for consideration based on [5, 8] and previous research are summarised in Table 5. Surges can occur in all parts of a PV system. A large part of research of the effects of lightning surges has been conducted on the behaviour of panels. The research conducted in [19] and [21–23] investigate this aspect. One factor considered is the strike point of lightning on the PV array. It was found that when lightning strikes directly on the edges of a PV array the induced overvoltages are higher than when striking near the centre of the array [19, 21]. Futhermore, when the strike point is asymmetrical to the plane of the panel a higher induced overvoltage is generated [22].

Table 5: Components of an internal LPS for PV systems

Internal Lightning Protection System
SPDs - selection and coordination
LPZs - evaluation of LEMP and induced overvoltages
Equipotential bonding - external and internal LPS
Cabling - DC and AC, induction loops, cable insulation
Separation distances - internal electrical equipment

The I-V and P-V characteristics of a polycrystalline panel were analysed in [23] when the panel was subjected to different lightning current impulses. The induced overvoltage across the panel was increased and it was observed that the performance of the module gradually degraded relative to an increase in the induced overvoltage. Analysis of a damaged panel from a nearby strike to a tree was carried out in [3]. The nearby strike caused a flashover to the panel with visible spark discharges seen on the panel backside. A thermal imaging camera was used to view the condition of the cells when exposed to direct sunlight. Although there was structural damage to the cells there were no signs of melted parts, including the frame of the panel, which is indicative of a surge condition. One interesting aspect to consider is the formation of streamers from a nearby lightning strike. Streamers from panels that do not become upward leaders to meet the downward leaders for a cloud to ground flash break down at high potential. This could have an effect on the overall performance and lifespan of the panel.

Another factor contributing to overvoltages in a PV installation is cabling. Induced overvoltages in the system increase with loop area [24]. It was shown in [17] that the positioning of the cable with respect to the PV structure influences the induced overvoltage in the cable. One method to assist in reducing cable loop dimensions, as presented in [18], is to use string inverters instead of a central inverter. The use of different types of inverters brings about a change in wiring configurations due to the termination points of the panels. The addition of micro-inverters could also be considered in this regard. The majority of research conducted on lightning effects on cabling makes use of modelling techniques for simulation purposes. This is due to the scale at which experiments must be conducted.

To reduce the overall effects of surges in a system, SPDs are used. The implementation of SPDs brings about the concept of LPZs [8]. Each zone requires a different class of SPD due to the different effect of lightning in that zone. There are shields created by the structure itself which minimize the electromagnetic effects inside the structure. These could differ from the protection zone on the outside where the PV array resides. There are additional standards such as the IEC 61000-4 and IEC 61643 detailed in [8] which aid in the selection and coordination of SPDs including the classes of SPDs required in the different zones. Simulation work has been conducted to study the effects of surges on the different parts of a PV system which include the DC and AC sides in [25–28]. It was found that surges caused by lightning do indeed have an effect on both the DC and AC sides of the system based on specific factors for medium- to large-scale systems.

Interestingly, there is not much consideration of the effects of lightning on energy storage systems which have become mainstream in local residential installations. The research done in the field of PV shows a lack of work done on the effects of lightning on storage. This is potentially an area with a considerable gap in technical understanding. There is also the concept of equipotential bonding which requires all PV equipment and SPDs to be bonded to the same equipotential bonding bar [16]. This is to minimize potential differences in the system. In [20] it was determined that interlinking the PV array and the distribution board (DB) reduced overvoltages in the system, however, SPDs are still required.

In the paper by J. Hernandez et al. [14], a comprehensive analysis of surge protection requirements is conducted in which all attributes of an internal LPS are addressed. The measures for protection against LEMP in a PV system, as detailed in [14], are summarised below:

- Grounding - a single earthing structure is required
- Equipotential bonding - bonding network with all equipment bonded to one bar
- Magnetic shielding - installation of spatial shields such as cable ducts
- Line routing - suitable cabling technique to reduce induction loop areas
- Isolating interfaces - isolation equipment requirements for sensitive electronic equipment
- Application of SPDs - selection and coordination of SPDs in the different zones

This methodology would bring about a well-designed internal LPS. A comprehensive guide to internal LPS design is also given by Dehn in [15]. The specific requirements of free-field PV plants and rooftop installations differ for both external and internal LPS designs. Continued research in these areas, as well as the risk assessment process, is undoubtedly required for the development of adaptive/specific standards for lightning protection of PV systems.

5. PROSPECTS FOR FUTURE WORK

Although research has been done in relation to lightning protection for PV systems, there are still many aspects to be investigated. For lightning damage to a structure, the risk assessment process from the IEC 62305-2 standard is followed. However, installing a PV system in a structure brings about the retrofitting of the physical attributes as well as electrical reticulation of the structure. This would differ for free-field PV systems where there is no previously existing structure. This may affect the risk assessment process for the structure where the integration of the PV system should be considered.

Considering the retrofitting of the PV system itself, if additional components are added at a later stage, such as more panels and hence a larger inverter, would a previously installed LPS be sufficient to manage the risk? PV system configuration could also play a role in lightning risk for off-grid, grid-tied and grid-tied with storage configurations. With regard to storage, there could possibly be added risk of loss of human life in addition to economic loss for a small-scale system. This is due to the installation location of storage inside the structure.

In terms of the external LPS, the rolling sphere method must be looked at in terms of the location of air terminations due to the tilted nature of a PV array on a flat roof and the question of shading on the modules. For the internal LPS, surge protection is applicable. Surges could affect any of the power electronic equipment, including battery-form storage, which again points to the question of risk. Cabling is considered in terms of overvoltages where the type of inverter such as string, central or micro-inverters may affect the cable length and arrangement for the installation.

Another consideration for surges through the system would be streamers developed on panels by a nearby strike. The breakdown of a streamer may damage the panel itself or offset a surge through the rest of the system. Regardless of all the aforementioned factors, lightning ground flash density may yet play the largest role in the analysis of lightning protection and risk assessment requirements for PV systems. This is due to the different scales of PV system which could range from small-scale rooftop to large-scale free-field utility installations.

6. CONCLUSION

Lightning incidents are common occurrences that have a direct effect on many facets. This phenomenon is still not fully understood but the continuous knowledge production in the field of lightning protection will aid in protecting living beings, structures and equipment. With the growing number of PV installations worldwide, lightning protection considerations play an increasing role. The understanding of the interaction between PV systems and lightning will come a long way in reducing economic loss, preventing harm and ultimately improving the prospect of PV technology growth. The continued work done will assist in the development of lightning protection standards for PV systems in a thriving PV market.

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