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Lightning Risk Assessment, Control and Protection Scheme Design for a Rooftop Photovoltaic System in the New Capital of Egypt

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ABSTRACT

The absence of an effective lightning protection system for photovoltaic (PV) systems can hinder their integration into networks. Outdoor PV installations are vulnerable to direct or indirect lightning strikes, resulting in damaging overvoltages that harm the PV structure. These systems, often situated on rooftops or open fields, face increased lightning strike risks due to their exposure compared to more sheltered setups. Lightning-induced surges can harm sensitive electrical components like panels, inverters, and wiring, leading to potential damage and downtime. The complexity of PV systems, with interconnected components, makes designing protection strategies challenging. Compliance with lightning protection standards is crucial to prevent damage, downtime, and financial losses. Implementing effective protection measures involves grounding, surge protection, and adherence to regulations. Lightning protection systems intercept strikes and safely direct electrical energy to the ground, safeguarding sensitive components and ensuring continuous power generation. The IEC 62305-2 standard guides lightning risk assessment and mitigation, aiding in evaluating risks, calculating damage likelihood, and designing protective measures. A case study focusing on the Arab African International Bank's rooftop PV system in Egypt illustrates the importance of lightning risk management in financial, operational, and regulatory contexts for solar projects. Risk assessment aims to identify vulnerabilities, implement mitigation strategies, and ensure safe, reliable system operation. By addressing lightning risks effectively, stakeholders can enhance system safety, reliability, and longevity while minimizing downtime and revenue loss associated with lightning strikes.

1. Introduction

As the global demand for clean and renewable energy sources continues to rise, photovoltaic (PV) systems have emerged as a cornerstone of sustainable energy solutions. PV technology harnesses sunlight to generate electricity, reducing reliance on fossil fuels and minimizing environmental impact. However, the effectiveness and longevity of PV systems can be significantly compromised by lightning strikes, making lightning protection a crucial aspect of their deployment. Sustainable energy is essential for addressing climate change and fostering environmental stewardship. By transitioning to renewable sources like solar power, we reduce greenhouse gas emissions and combat air pollution. PV systems are particularly valued for their ability to convert sunlight into electricity with minimal operational costs and zero emissions during their operation. As more individuals, businesses, and governments invest in solar energy, the role of PV systems in achieving energy sustainability becomes increasingly critical. Despite their benefits, PV systems are not immune to natural hazards. One of the most significant risks is lightning. PV systems, often installed on rooftops or open fields, are highly exposed to lightning strikes. A direct hit or a nearby strike can cause severe damage to the system’s components, including solar panels, inverters, and wiring. This damage can lead to costly repairs, system downtime, and reduced energy production, undermining the very benefits of adopting solar technology [1].

One of the most serious issues with electrical networks has always been designing an efficient protection mechanism. This mechanism should be designed to be simple and cost-effective, while also being able to immediately identify any abnormal state to reduce network equipment damage (reliability). additionally, the system should ensure selectivity by isolating solely the affected area [2], [3]. Lightning strikes on PV supports are a frequent occurrence, prompting extensive research into protection related to lightning systems for PV systems. When lightning surges occur, the closed system circuity of a PV mechanism can generate a high-induced overvoltage, resulting in harm to both the structure of PV and the combined frame [4], [5].

PV structures are typically situated outdoors and installed on the construction roofs of the structures to maximize sun exposure, which also heightens the likelihood of getting a lightning strike. The strikes of Lightning are a leading contributor to the damage of numerous power system components worldwide lightning strikes that happen between two clouds' charges or between clouds' charges and air charges are known as cloud flashes (are a type of lightning discharge that occurs within or between clouds, rather than between a cloud and the ground. They are often associated with the complex electrical processes occurring within thunderstorms), whereas lightning strikes that happen in space between a cloud and the ground are known as ground flashes (are a type of lightning discharge that occurs between a cloud and the ground. They are among the most familiar types of lightning and are characterized by their visible connection to the Earth's surface) [1], [3].

To implement suitable measures of protection against external surges, it is essential to conduct a risk management study according to IEC 62305-2 and to thoroughly examine the system of protection related to the lightning system. Neglecting adequate protection against lightning can cause delays in the return on investment for PV systems. Therefore, it is strongly advised to consider protection measures that strike a balance between technology and economics. In fact, designing and implementing an effective LPS is crucial for ensuring the safe operation of PV installations, which represents substantial capital investments [5], [7]. Buildings using PV systems do not lead to an elevated risk of lightning strikes, thereby making it difficult to directly justify the necessity for lightning protection solely depending on a photovoltaic system's presence. Moreover, it is essential to note that there is a heightened potential danger to the electrical systems in the instance of a strike of the building. This is primarily due to connections of PV lines within a building's risers and raceway runs, which can result in significant conducted and radiated interferences caused by lightning currents. Protecting the photovoltaic panels and the operation building from fire damage, as well as the electronic and electrical appliances from the effects of lightning electromagnetic impulses, is the aim of a solar power plant [6], [12].

The size of PV systems is growing along with the steady increase in the amount of electricity generated by PV sources. The systems' greater size exposes them to a higher range of atmospheric conditions in open-field situations, which may make them more susceptible to lightning discharges. PV arrays, which are collections of PV modules, are frequently outfitted with lightning protection systems to prevent damage from direct lightning strikes. However, even if lightning hits nearby, it can still have significant repercussions and potentially harm the structures of the system. Consequently, studying any effect of lightning on PV modules is critical for ensuring their safety. When engineers have a thorough understanding of the voltage caused by lightning and its distinct properties, they can protect photovoltaic panels throughout the design process [7], [9].

Lightning protection systems, such as lightning rods, conductors, and grounding systems, help to safely channel the electrical energy from lightning strikes away from sensitive PV components. This prevents potential damage and extends the lifespan of the system. Ensuring that PV systems are protected from lightning strikes helps maintain their operational efficiency. Reduced downtime and fewer repairs mean a more reliable source of clean energy, contributing to a stable and consistent energy supply. Investing in lightning protection can save significant costs overall. By preventing damage to PV systems, businesses and homeowners avoid expensive repairs and replacements, making solar energy a more economically viable option. Adhering to standards and regulations for lightning protection, such as those outlined in IEC 62305-2, ensures that PV systems meet safety and performance criteria. Compliance with these standards also helps in obtaining necessary insurance and certifications [6], [1].

PV systems are often installed in locations highly exposed to environmental elements, including lightning strikes. Whether mounted on rooftops or in open fields, these systems are at risk of being hit by lightning, which can have severe consequences. A direct lightning strike or a nearby strike can induce high-voltage surges, causing damage to sensitive components like solar panels, inverters, and wiring. This can lead to costly repairs, system outages, and reduced energy production. Risk assessment involves evaluating the potential hazards and vulnerabilities of PV systems to lightning strikes. By conducting a thorough risk assessment, stakeholders can identify specific risks associated with their installations and develop strategies to mitigate these risks. Effective lightning protection is essential for maintaining the integrity and functionality of PV systems. Key aspects of lightning protection include Lightning rods or air terminals can intercept lightning strikes and direct the electrical energy safely into the ground. Also, Proper grounding is vital to dissipate the energy from a lightning strike, preventing it from causing damage to the PV system. And surge protective devices protect electrical components from voltage surges caused by lightning strikes, reducing the risk of damage and system failure [3], [5].

Studying risk assessment and lightning protection for PV systems is crucial for ensuring their longevity, reliability, and financial viability. By proactively identifying potential risks and implementing effective protection measures, stakeholders can safeguard their investments, ensure consistent energy production, and support the broader goals of sustainability and environmental stewardship. As the adoption of PV technology continues to grow, prioritizing these aspects will be key to realizing the full potential of solar energy and maintaining its role in a sustainable energy future [5], [9].

In the literature, Ahmad et al. proposed that approximately 26% of reported incidents in PV systems are attributed to lightning. Additionally, studies have shown that PV structures can suffer considerable damage from lightning strikes (LS) in close proximity to the system, which occur more frequently than direct strikes [8]. Rakov and Rachidi. recent research executed to assess the influence related to indirect strikes of lightning on the design of Photovoltaic structures and protection systems. Since PV systems are usually installed at a low height of a few meters, any increase in voltage caused by electric induction is usually unimportant and disregarded in normal circumstances. Thus, magnetic induction is the primary factor controlling this phenomenon [9]. Hossain and Ahmed proposed the utilization of a three-dimensional finite differences time domain technique and a slim wire representation of both the wire of DC and solar panel structure to compute the voltages produced by a vertically oriented channel of lightning. Furthermore, a semi-analytical model was employed to account for the complex shape of the lightning channel and assess the voltages induced on the structure of PV due to indirect lightning strikes [10]. E Pons and R Tommasini. proposed a method for a practical scenario involving Several kinds of protection of lightning systems and strikes. This method includes approximate formulas to estimate induced voltages and currents [11]. Zhang et al.

proposed utilizing the modified mesh current technique and introduced a time-domain multiport thin wire system model for analyzing the impact on PV structure from lightning. The model was assessed through the Gmsh software to examine different factors like lightning peak current, building height, resistivity, and distance. The findings revealed that higher soil resistivity leads to reduced peak values of generated overvoltage. Additionally, more overvoltage peak levels were obtained when the separation between the array of photovoltaic cells and the protective mechanism was increased [12]. Tu et al. investigated the effects of the resistivity of soil, the value height of the building, lightning current amplitude, and separation distance to the outdoor protection equipment on induced lightning overvoltage on the top of the roof photovoltaic electrical network. The generalized modified mesh current approach was utilized to model the lightning transient behavior of the arrays of solar panels. The conclusion of the study is that higher resistivity of the soil leads to higher induced overvoltage. Moreover, if the lightning strike happens near the solar array's output cables and metal housing, the induced over voltages are also higher. On the other hand, reduced induced overvoltage occurs when the protection devices are positioned farther away from the rooftop solar panels [13]. Sabiha et ala research project to investigate the occurrences of backflow lightning overvoltage in the power plant of photovoltaic which is situated in Saudi Arabia. He also suggested a design for the system of grounding for PV structures that could help mitigate this lightning overvoltage. The evaluation of this proposal was evaluated by using ATP/EMTP software and COMSOL Multiphysics. The research revealed that the backflow lightning overvoltage also any amount of energy absorbed by the surge protection device was remarkably raised at the struct panel. However, the values reduced as the separation distance from any affected panel increased. Furthermore, both parameters escalated with an increase in the resistivity of soil. As a result of implementing a modified array grounding system, the absorbed energies and backflow lightning overvoltage could be reduced to an acceptable level [14]. Adekitan and Rock were investigated the efficacy of different systems of air termination cables and rods in various structures. The study utilized a dynamic electro-geometrical model to analyze the impact on the time of computation for employing two definitions of space volume. The findings revealed that the effectiveness of the intercept was influenced by the volume of space, also the study highlighted strategies to minimize computation time [15]. Kim et al. proposed using the PSCAD/EMTDC software for a study aimed at simulating a connection to the grid of the PV mechanism and analyzing its behavior as well as performance under control when connected to the grid. PSCAD/EMTDC is a software package specifically designed to analyze electrical networks and equipment in a transient manner. Through simulation analyses, various scenarios like power regulation performance, anti-islanding, response to grid disturbances, and current harmonics were assessed to determine how well the connection to the grid of the PV mechanism functioned [16]. Nanaki’s et al. a study to evaluate the efficiency of single-crystalline silicon PV structures when subjected to the standard impulse of the lightning voltage strokes. The researchers assessed the array's performance by analyzing P-V and I-V characteristic curves after the lightning strikes and compared the results to those of a reference module. The study findings showed that the photovoltaic module remained unaffected in terms of power output and mechanical functionality when exposed to the specified 12 kV peak voltage outlined in IEC 61730-2. In addition, the researchers determined that an even higher peak voltage of 144 kV was necessary to cause mechanical, electrical, and thermal failure in the solar panel [17]. Mohammed et al. proposed a study that analyzed the impact of lightning surges on a hybrid photovoltaic-wind structure connected to the grid. The study utilized PSCAD/EMTDC software to inject surges of lightning for Several kinds and magnitudes within the power station in three distinct locations. The models were performed both with and without the presence of lightning protection systems (LPS). Results revealed that the absence of lightning surge arresters had detrimental effects on the hybrid power plant, with transient currents and over voltages causing destruction [18]. Ittarat et al. a research study utilizing a computer program to assess if a lightning protection system is necessary. The researchers gathered information concerning protection systems of lightning for photovoltaic power stations to advance the software program. To evaluate its effectiveness, they utilized information from a 25 kWp photovoltaic structure located in Thailand and discovered that the power plant faced an average risk of 4.15 lightning strikes per year [19]. Lewis et al. proposed A scheme for a significant two-stage photovoltaic structure that was both cost-effective and accurate. The model was designed specifically for incorporating large-scale grids into the network of low-voltage distribution. It employed a linear state-space technique, which was derived from the detailed electromagnetic transient model of the photovoltaic structure [20]. Sun et al. proposed research that utilized the finite-difference time-domain method to analyze any effects of the induced voltage of lightning on photovoltaic structures. The model not only accounted for electromagnetic wave propagation but also considered the properties of the surrounding environment. The researchers explored the effect of lightning-induced voltages on photovoltaic structures situated on a variety of terrains such as mountains, lakes, and flatlands. Specifically, the mountainous region was further subdivided into V-shaped, trapezoidal, and triangular terrains. The study's findings indicated that the induced voltage was affected by the conductivity of the ground. Terrains with higher permittivity and lower conductivity exhibited heightened voltage, which increased with the elevation of the PV system [21]. Zhang et al. proposed research focusing on transient behavior for a photovoltaic (PV) power plant in case of any strike of lightning on any nearby line of service. The study researchers analyzed damages of three types which included arcing through metal parts, malfunction of PV inverters and bypass diodes. The simulation study successfully generated induced voltage measurements that matched the actual conditions of the operational plant [12]. Sun et al. employ an advanced model of three-dimensional to assess the electromagnetic transient related to the array structure. The model's accuracy was verified by comparing it with the data obtained from experiments, as well as existing research. Furthermore, the research also investigated various factors, including the point of the lightning strike, the angle at which the PV panels were mounted, the lightning channel's form, as well as The PV frame's design, to determine their influence on induced voltage. Moreover, the study developed and compared three different installation modes for PV arrays located in mountainous areas [22]. Zhang et al. how the contact lightning operation of the solar cell mechanism can be enhanced by considering various factors such as the type of PV module, mounting technique, and proper organizing of Direct Current wires. Additionally, the study investigated the transient characteristics of a frameless thin-frame photovoltaic structure [13]. Q Sun et al. proposed that the number of grounding rods influences the behavior of the transient response. When there are more grounding legs, the overvoltage decreases. The existence of an equipotential bond creates extra paths for the discharge of lightning current, which aids in lowering the voltage. Nevertheless, it also increases the PV structure's overall hazards. Including an extra leg also influences the overall performance of the system [23]. Mohammad. proposed a developing software solution that makes it simple to run complicated calculations the lightning risk assessment that determines if the LPS installation is necessary or not. and choose the best Lightning Protection System for PV plants according to IEC62305-2 [24]. Pomponi and Tommasini proposed a study that aims to evaluate the voltages caused by lightning discharges and establish whether lightning protection measures are necessary based on risk analysis and protection costs [25].

The integration of sustainable energy solutions, such as photovoltaic systems, is a crucial step towards a greener future. However, to fully realize the benefits of solar power, it is essential to address potential risks, including lightning strikes. By investing in robust lightning protection measures, which can safeguard PV systems, enhance their reliability, and ensure their contribution to a sustainable and resilient energy landscape. As continue to embrace renewable energy technologies, prioritizing their protection will be key to achieving long-term success and sustainability in the global energy transition [7], [12].

The study will be on a real case project that is under implementation which is in the new capital of Egypt. This project contains PV modules on the roof of the building. a full detailed study will be made for lightning risk management with all factors subject to the British Standard 62305-2. The most important benefit of this paper can be described:

- Risk management study for the structure.
- Analysis of the result of risk management to know the need for LPS.

- If applying LPS, the recommended level of protection will be concluded.
- The result will discuss the calculated risk compared with tolerable risk and lightning protection level.

The paper organization is structured as follows: Section 2 presents the methodology that contains basic concepts and risk management analysis. Section 3 clarifies the design concept of lightning. Section 4 introduces the studied system, and its calculations are presented in Section 5. Section 6 clarifies the discussions of any results. Section 7 discusses conclusions.

2. Methodology

2.1. Basic Concepts

Lightning overvoltage protection is a critical component of PV power plant protection methods, particularly Among regions where stormy and overcast weather. If the overvoltage problem is not identified as well as fixed, the structure of the photovoltaic equipment might be destroyed, increasing the return on investment. PV systems suffer from both direct and indirect over voltages. In the previous situation, The PV mechanism is struck by lightning., but in the current situation, Lightning damages cables that enter the structure or strike adjacent electrical wires or cables. Overvoltage damages equipment and could represent a fire hazard if they above the impulse withstand voltage [26], [8].

Surge protection devices (SPDs) are required to properly route over voltages to the ground, even when they are minor. When it comes to an overvoltage, an SPD's impedance significantly drops, creating a low-impedance path to the ground, whereas it exhibits a high impedance at the nominal voltage [26], [7].

An LPS is constructed from both external and internal protective systems. The photovoltaic structure is safeguarded from strikes of direct type with the aid of the system of air termination, system of the down-conductor, and system of earth termination. These systems work together to intercept the lightning, conduct the charge safely to the level of the ground, and distribute the charge within the level of the ground, ensuring external protection of the PV system. The system of the PV structure internal protection system stops any potential sparking within the structure by either implementing preserving a safe separation distance among the parameters of the System protected subject to lightning system and other conductive components of the structure [26], [4].

In IEC 62305-1, there are four levels of an LPS that correlate with the electrical attributes of an expected strike. These levels are associated with four categories of an LPS (I, II, III, and IV) Those are outlined in the British standard IEC 62305-3. Every level has lightning current parameters, both minimum and maximal [27], [6].

2.2. Comparison with Other Protection Methods [5], [3]

1. Grounding Systems Alone

   Simple grounding systems involve connecting electrical systems to the earth to dissipate electrical faults, inexpensive and easy to implement. Also, Provides limited protection and does not prevent lightning strikes or surges effectively.

2. Shielding

   Shielding involves enclosing sensitive equipment or structures in conductive materials to block electromagnetic interference, effective for protecting against electromagnetic interference (EMI) and radio frequency interference (RFI), also, Does not protect against direct lightning strikes or high-energy surges and can be costly and complex to install.

3. Transient Voltage Suppression (TVS) Diodes

TVS diodes are used in electronic circuits to protect against transient voltage spikes, Provides fast response to transient voltages and is effective for protecting individual components. also, not suitable for large-scale or high-energy protection needs and typically used in conjunction with other protection methods.

- LPS: Best for protecting entire structures from direct lightning strikes. It offers comprehensive coverage but comes with higher initial costs and visible components.
- SPDs: Ideal for protecting electrical and electronic equipment from voltage surges. They are cost-effective and flexible but do not protect against direct lightning strikes.
- Other Methods: Provide varying degrees of protection against specific types of interference or faults but do not offer the same level of protection against lightning and surges as LPS and SPDs.

In practice, a combination of LPS and SPDs is often used to provide both direct lightning protection and surge protection for sensitive equipment, ensuring comprehensive safety and reliability.

2.3. Risk Estimated Analysis as per IEC 62305-2

To determine if a structure, specifically a PV system, needs protection against lightning strikes, a risk assessment must be conducted following the guidelines stated in Standard IEC EN 62305-2. The process for evaluating the risk is described in the following paragraph [28], [2].

To comprehend the factors that contribute to the risk associated with a structure requiring protection, several concepts need to be clarified. Firstly, it involves determining the exact location where a lightning strike is most likely to occur. The resulting damage to the structure will vary depending on this location. Subsequently, this damage can lead to losses within the structure. These losses are quantified into a numerical value, known as the risk number (R), which indicates the relative significance of the potential annual loss. The risk number is then compared to the tolerable risk, depending on the type of loss. Based on this comparison, appropriate measures for protection should either be implemented or not [29], [9].

2.3.1. Definition of Key Terms (Damage and L oss)

As the lightning current strikes a point into the structure, the flash-striking location might be referred to as the source (S) for potential damage [30], [31].

Source of damage

Four distinct sources of damage exist, which are S_1 represents a strike of lightning to any building structure. S_2 is the strike of lightning near any building structure. S_3 is the strike of lightning to a service, and S_4 represents the strike of lightning near a service.

Types of damage

As per the features of whatever structure needs protection, the Lightning strike could result in damage. The kind of construction, the components and applications, the kind of service, and the safety precautions offered are some of the important features. It is essential to differentiate between the types of damage that can result from lightning flashes for the practical uses of this risk assessment. The types of damage can be divided as follows: D_1 denotes injury from electric shock to organisms. D_2 is physical harm. D_3 represents electricity and electronic system failure. A structure's damage from lightning may only affect a portion of it or it may involve the entire structure. Additionally, it could involve the buildings nearby.

Types of loss

The characteristics of the structure and its materials indicate the possibility of any kind of loss. These kinds of losses need to be considered. L_1:is the loss of life for humans (such as injuries as well as any other injuries resulting from lightning strikes near the building structure). L_2 is the loss of service to the community (covers water, gas distribution, electricity, as well as telecommunications installations. This applies to similar cases where a damaged building—like a power plant—will cause a loss for many individuals who are outside the building). L_3 is the loss of cultural heritage (which is subject to museums, historical building structures, and any locations designated as national historic sites where the loss of a portion would have a significant impact on the cultural value). L_4 represents the loss of value economically.

2.3.2. Risk Components

A structure may need to take the following risks into account [31], [2]. The necessary risk components (partial risks based on the source and type of damage) must be specified and derived to evaluate risks, R.

The total of any risk, R, is the sum of its components that make up risk. The risk components can be categorized based on the type of harm and its source when calculating a risk. Fig. 1 outlines the different types of risk of losses [29]. Typical values of tolerable risk, R_T, are cleared in Table 1. For types of risk, the types of loss are linked to these values [31]. Procedure for deciding the need of protection Fig. 2.

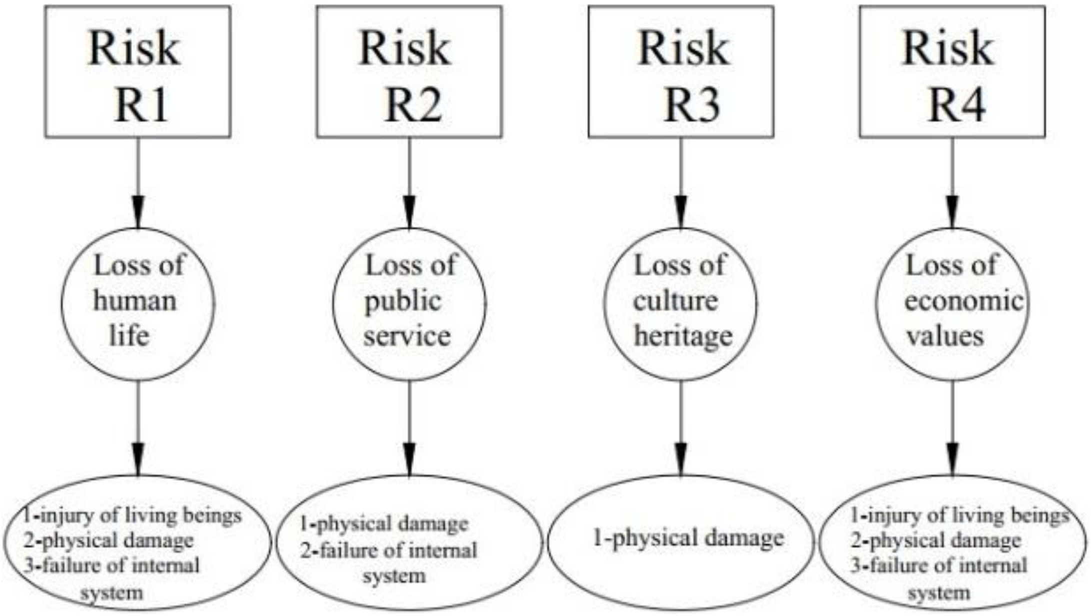

Fig. 1. Risks and types of loss associated with various damage types

Table 1. Average acceptable risk values (R_T)

	Types of Loss	$R_T\ (year)^{-1}$
L_1	Human life loss	10^{-5}
L_2	service to the public loss	10^{-3}
L_3	Heritage of culture loss	10^{-4}

In general, the cost-benefit analysis provided in Annex D should be used for the value of economic loss (L_4). In case of the absence of information for this review, the value of allowable risk, $R_T = 10^{-3}$, might be applied [31]. Thus, a process that leads to the final risk value may be identified [29]. A structure's total potential risk is estimated as [26]:

$$R = R_1 + R_2 + R_3 + R_4 \tag{1}$$

$$R_1 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z \tag{2}$$

$$R_2 = R_B + R_C + R_M + R_V + R_W + R_Z \tag{3}$$

$$R_3 = R_B + R_V \tag{4}$$

$$R_4 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z \tag{5}$$

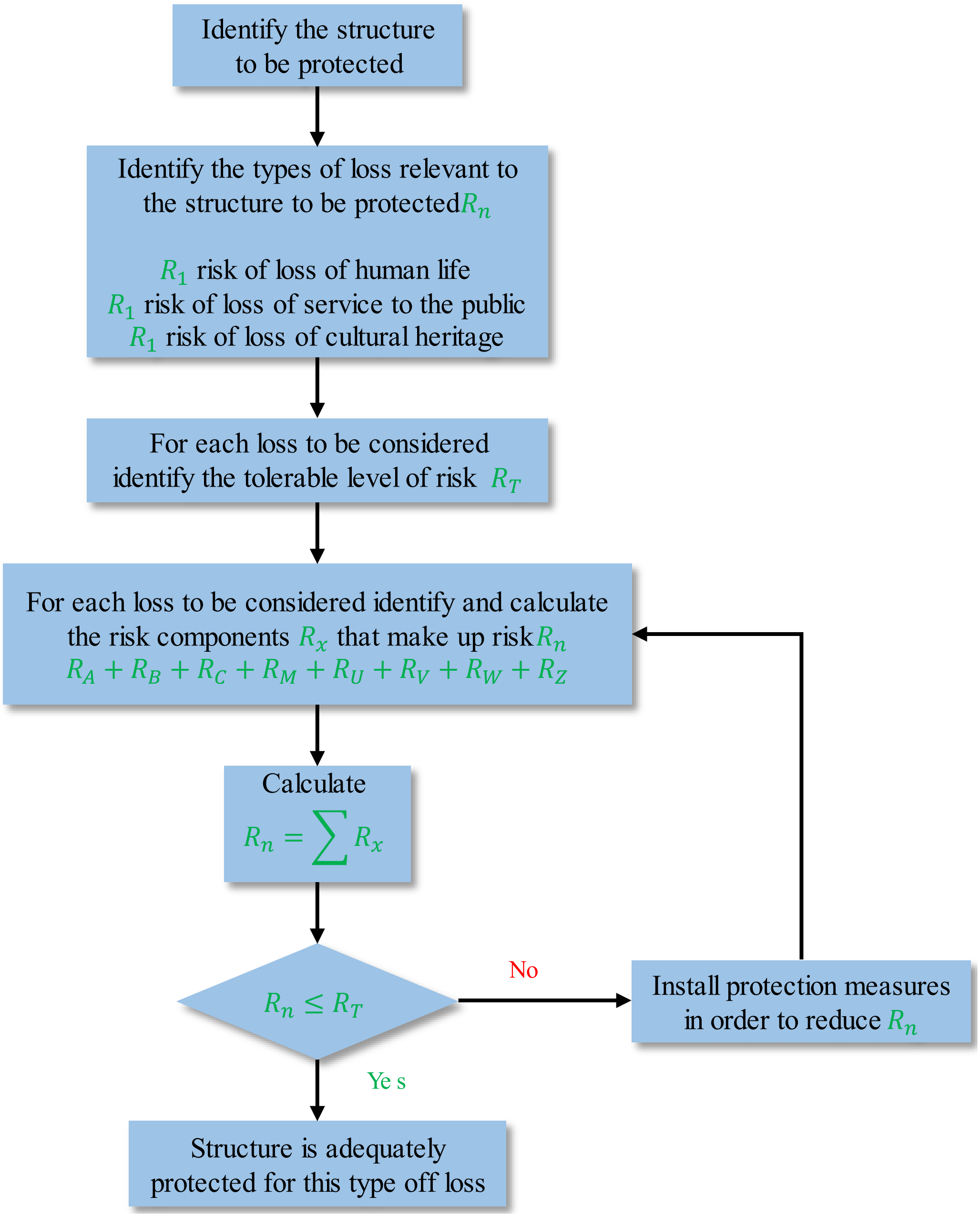

Fig. 2. Procedure for deciding the need of protection [1], [9]

Where R_A refers to the damage caused to organisms by step and contact voltages in case of a strike of direct form. R_B is concerned with the physical harm created by sparkling within the building structure, which, in the event of a direct flash, causes an explosion or fire. R_C corresponds to the internal system failure brought on by electromagnetic impulse caused by direct lightning, in the event of a strike of direct form. R_M corresponds to the inner system malfunction brought on by electromagnetic impulse in case of a strike of indirect form. R_U refers to the harm caused to organisms by step and contact voltages in the event of a strike connected by the line to the building structure. R_V is concerned about the harm caused by sparkling throughout metal components as well as outer installations because of the current of lightning that is transmitted among incoming utilities within a strike that flashes to a connected line to the building structure. R_W relates to a failure of the inner mechanisms produced by generated induced overvoltage on receiving network lines as well as communicated to the building structure in the event of a strike to a connected line to the building structure. R_Z relates to a failure of the inner mechanism produced by generated induced an overvoltage on receiving network lines and communicated to the building structure in the event of a flash near the connected line of the building structure.

2.3.3. Tolerable Risk

Tolerable risk: This refers to the level of risk that is considered acceptable and manageable within a given context. Tolerable risk is the level of risk that an organization or individual is willing to accept to achieve their objectives without compromising safety or well-being.

Partial risk: Partial risk refers to the portion of risk that is not fully mitigated or addressed within a risk assessment. It typically represents the residual risk that remains after controls and measures have been implemented to reduce the overall risk level. efforts should be made to minimize it wherever possible. Every risk component from R_A to R_Z is determined as [11], [7].

$$R_x = N_x P_x L_x \tag{6}$$

Where N_X is the number of risky incidents that occur each year. P_X is a possibility related to the building structure may be damaged. L_X is the consequence of losses. To assess any risk, the following procedures must be conducted: [31].

- Estimation of the parts of the risk R_x.
- Computation of the detected risk components R_x.
- Computation of the overall risk R.
- Consideration of the risk of acceptable value R_T.
- Comparing an acceptable value along with risk R_T.

Through a comparison between the computed risk value and an accepted risk value, R_T

-in case of the following results:

- $R \leq R_T$, the protection of lightning is unnecessary
- $R > R_T$, R should be reduced to acceptable values by implementing protection measures. ($R \leq R_T$)

3. Lightning Design Concept

The objective of an LPS is to safeguard buildings from possible mechanical or fire-related harm, while also ensuring the safety and well-being of individuals, preventing any potential injury or loss of life [27]. The system of protection subject to lightning consists of an outdoor and an indoor mechanism of Lightning Protection. The outdoor mechanism consists of a system of air terminating, a system of earth terminating and a system of down conductors. The indoor mechanism consists of a device of surge protection.

3.1. Air Termination System

The primary objective of the system of air terminating is to safely redirect strike to the Earth's surface, rather than allowing it to strike the ground at random. To accomplish this, the system utilizes air terminals which are specified in the IEC 62305 standard. These components are strategically placed on and around structures to create protective zones that safeguard against indirect and direct strikes of lightning. The rolling sphere technique is employed for computing the boundaries for these protective zones. Location subject to air terminal defined by the LPS class [32], [3], as indicated in Fig. 3.

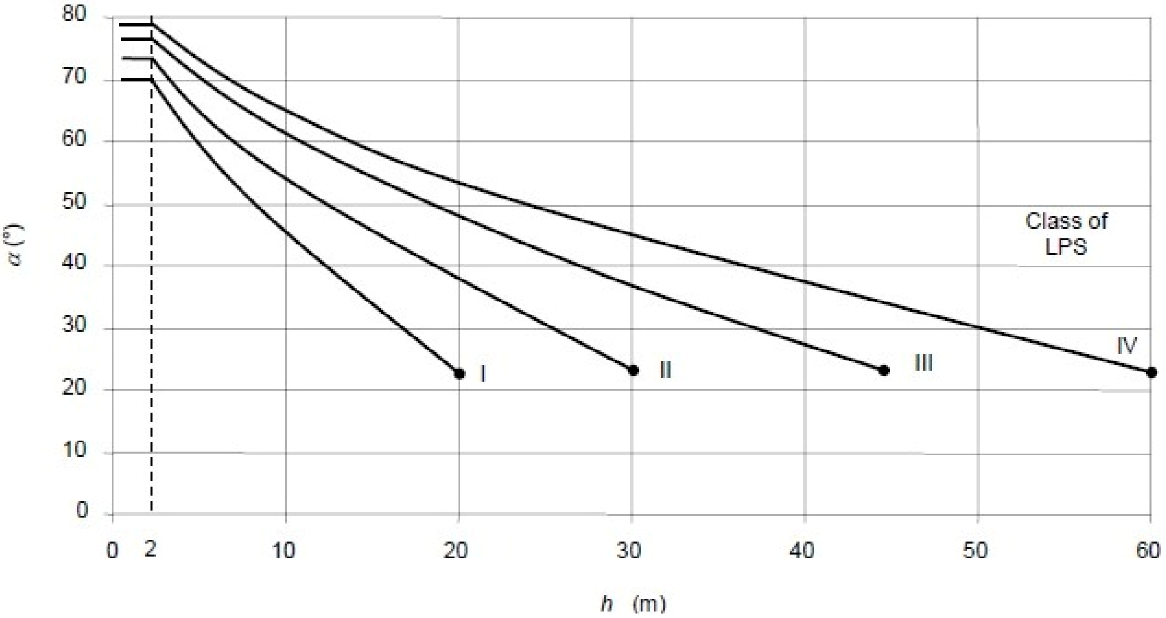

Fig. 3. An angle of protection compatible with the LPS class, based on (h), which is the height of the air-terminating rod just higher than the corresponding guideline surface

Note: for h values below 2m, the angle remains constant.

The electro-geometric model acknowledges that the distance of strikes, dictated by the lightning current's amplitude, is an attractive influence function related to the air termination system. length of the stepped leader's final jump determines the striking distance since its potential is higher than the final air-to-ground gap's breakdown resistance. The determination of the distance is based on the rolling sphere radius. an electro geometric simulation model assumes that a specific distance at which lightning strikes is linked to a minimum peak current for the first stroke. This model is implemented by the method of rolling sphere. which utilizes a process for rolling a theoretical sphere with a predetermined radius across the network of the air-terminating rods. The building structures, equipment, as well as other mechanisms located beneath the sphere's curved surface are shielded from strikes of direct type due to the lifting of the sphere by the air-terminating rods. However, any structure that meets the imaginary sphere is not afforded any protection. Depth of penetration of a rolling sphere shown in Fig. 4.

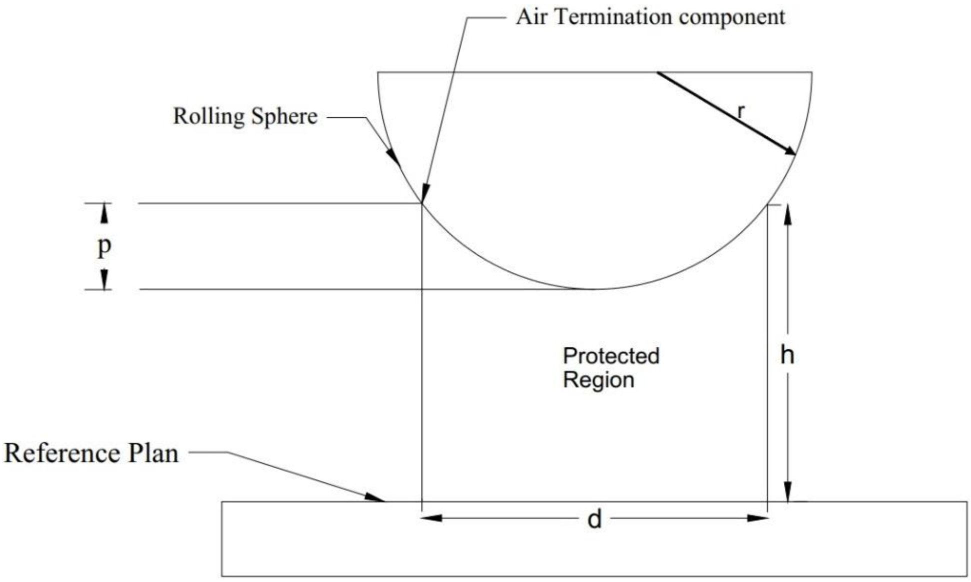

Fig. 4. Depth of penetration of a rolling sphere

Where *R* represents the rolling sphere radius. *d* is the distance between components of an air terminal separated. denotes the height of the air terminal components. And *p* denotes the penetration depth of the sphere. The following equation for evaluation of the penetration depth of the sphere:

$$p = r - \sqrt{r^2 - \left(\frac{d^2}{2^2}\right)} \tag{7}$$

Then, the following formula is used for evaluation the radius of the sphere.:

$$r = 10I^{0.56} \tag{8}$$

Where *I* is the minimal peak current (kA). To obtain the required space for components subject to the protection of lightning system to provide the protection required against the strike of direct lightning, as shown in Table 2, the radius of the rolling sphere in the electro geometric model is derived by taking the minimum values of the amplitude of the lightning current for each of various LPLs. The LPL, which indicates the rolling sphere radius, determines the air terminal height above the protected structure. As seen in Fig. 3, To ensure that the protected structure does not meet the rolling sphere, the air terminal system's height should always exceed the depth of penetration of the rolling sphere.

Table 2. The corresponding minimum values of lightning and the rolling sphere radius are related according to the protection level of lightning

Interception criteria		**LPL**			
Criteria	Unit	I	II	III	IV
Minimum peak current (*I*)	KA	3	5	10	16
Rolling sphere radius (*r*)	m	20	30	45	60

3.2. Down Conductor System

The system of down conductors is composed of conductors of electricity strategically placed on an object to ensure that the current of lightning is safely transmitted to the system of earth termination. Such a setup effectively reduces the possibility of flashing occurring to other parts of electrical conduction. according to IEC 62305, down conductors must be set up to decrease the possibility that the LPS may sustain damage from lightning currents. A minimum of two down conductors must be used, and they must be arranged with equal spacing around as shown in Table 3.

Table 3. IEC 62305-3 proposed down conductor separation distance

Class of the system of lightning protection	**Typical distances (m)**
I	10
II	10
III	15
IV	20

3.3. Earth Termination System

The primary function of the system related to earth termination is as follows:

- Efficiently absorb the energy of lightning surge sent through the down conductors of the system of lightning protection.
- Ensure that faults and surges subject to electrical are effectively dissipated to reduce the risk of damage related to humans of both "step voltage" and "contact voltage."
- Bond of electrical conducting parts properly to establish an equipotential plane during strikes of lightning.

3.4. Surge Protective Device (SPD)

When lightning strikes a power or signal line, it creates a lightning electromagnetic impulse (LEMP). This impulse occurs due to the connection or voltage induction caused by the lightning strike, resulting in overcurrent and/or overvoltage defined as a surge. Lines entering a structure must be fitted with protection against lightning's destructive effects to shield them from lightning-induced transient voltages. Lightning electromagnetic impulse protection methods (SPM) must be used to reduce surge current or deflect transient voltages.

IEC 62305-4 standard using a worst-case method when sizing SPDs if 50% of Lightning related current passes throughout the ground and 50% returns through the equipotential bonding SPD(s) when current sharing between conductors is not specifically calculated. Utilizing the maximum current relating to the LPS class, the injected current for SPD selection is computed. SPDs that are subject to direct lightning strikes and are placed at the structure's line input must be rated at 50% of the class of LPS's maximum current rating, as specified in Table 4.

Table 4. LPS class maximum current rating

Class of the system of lightning protection	Total surge protection device Current of surge (Wave Form=10/350 µs)
I	100 kA
II	75 kA
III	50 kA
IV	20 kA

3.5. Separation Distance of the Outdoor for the System of Lightning Protection

To create electrical insulation between the air-termination or down-conductor and the structural metal parts, metal installations, and internal systems, it is possible to establish a separation distance, denoted as s. The value of s can be calculated using the equation provided [32]-[34].

$$S = \left(\frac{K_i}{K_m}\right) K_C L \tag{9}$$

Where:

- K_i: Coefficient based on the level of the protection system of lightning.
- K_m: Coefficient based on the insulation of electricity for the material.
- K_C: Coefficient based on the lightning current which flows in the down conductor.
- L: Refer to separation distance represents the measured length in (m).

Through the down-conductor or the air-terminal. It extends from the point where that distance of separation is determined to the closest earth termination or equipotential bonding point.

4. Studied System

The Arab African International Bank, located in Egypt's new capital, is a prominent financial institution in the region. It is situated at latitude 30°00'00"N and longitude 31°45'00"E. The bank plays a crucial role in driving economic growth and development. It provides both business and retail banking services, among other banking services, investment banking, as well as trade finance. The Arab African International Bank is known for its commitment to providing innovative financial solutions and excellent customer service. Additionally, its banking facilities, the bank as well as environmentally conscious, as evidenced by its photovoltaic (PV) system. With a module tilt of 0° and module azimuth of -166.6°, the PV system harnesses solar energy to reduce the bank's carbon footprint and contribute to sustainable energy practices. Several factors can impact the performance of a PV system:

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- Solar Irradiance: The amount of sunlight hitting the panels, which varies with geographic location, time of year, and weather conditions. Higher solar irradiance leads to higher energy production.
- Panel Efficiency: The ability of the PV panels to convert sunlight into electricity. More efficient panels produce more electricity for the same amount of sunlight.
- System Losses: These include losses from shading, dirt or debris on panels, temperature effects, and inefficiencies in the inverter and wiring. For example, high temperatures can reduce panel efficiency, while shading from nearby objects can decrease energy capture.
- Maintenance: Regular maintenance is crucial for optimal performance. Dust, dirt, and other obstructions can reduce panel efficiency, and periodic cleaning and inspection help maintain system performance.
- Technical Issues: Faults in components such as inverters, wiring, or connectors can impact overall system efficiency. Monitoring systems can help detect and diagnose these issues.

Photovoltaic (PV) systems, which convert sunlight into electrical energy, and lightning protection systems, designed to protect structures from lightning strikes, need to work together to ensure both operational safety and system efficiency. Here is a comprehensive look at how these systems complement each other [13], [9]. Study case data sheet for PV system shown in Table 5.

- Understanding the Risks
  - Lightning Risks: PV systems, being elevated and often installed on rooftops or open areas, are vulnerable to lightning strikes. Lightning can cause significant damage to PV panels, inverters, and wiring, potentially leading to system failure or fire hazards.
  - System Vulnerabilities: PV systems have sensitive electronic components that can be damaged by the electrical surges from lightning strikes. Moreover, the risk of fire increases if lightning strikes cause electrical faults or system damage.
- Integration with PV System Design
  - System Layout
    - Purpose: Proper system layout ensures that the lightning protection measures do not interfere with the PV system's performance.
    - Implementation: Position lightning rods and grounding systems in a way that they do not obstruct sunlight exposure or reduce the efficiency of the PV panels. Ensure that the grounding system is designed to integrate seamlessly with the PV system's support structures.
  - Regular Maintenance
    - Purpose: Regular maintenance ensures that both the PV system and lightning protection measures remain effective over time.
    - Implementation: Perform periodic inspections of grounding connections, SPDs, and lightning rods. Check for signs of wear or damage and ensure that all components are functioning correctly.
- Benefits of Integration
  - Enhanced Safety
    - Purpose: Protecting the PV system from lightning strikes reduces the risk of electrical fires, equipment damage, and potential hazards to occupants.

  - Implementation: With effective lightning protection measures, the risk of lightning-related damage is minimized, ensuring the safety of both the system and the building.
- Improved System Reliability
  - Purpose: Proper lightning protection enhances the reliability and longevity of the PV system.
  - Implementation: By preventing damage from lightning strikes, the PV system operates more reliably, reducing downtime and maintenance costs.
- Increased Efficiency
  - Purpose: A well-protected PV system maintains its efficiency by avoiding disruptions and damage caused by lightning.
  - Implementation: Ensuring that lightning protection measures are correctly integrated helps maintain the system's performance and energy production capabilities.
- Cost Savings
  - Purpose: Investing in lightning protection reduces the potential costs associated with repairs and system downtime.
  - Implementation: Effective protection reduces the likelihood of expensive repairs or replacements due to lightning damage, leading to long-term cost savings.

Table 5. Study case data sheet for PV system

Part	PV array characteristics		PV module specifications	
	Array1 Array3	Array2 Array 4	Part	Specifications
Number of PV modules	162 units	64units	Manufacturer	Jinko solar
Nominal (STC)	87.5 kWp	34.6 kWp	Model	JKM540M-72HL4-V
Modules	9 strings x 18 series	4 strings x 16 series	Unit Nom. Power	540 Wp
Max. power (P_{mpp})	79.9 kWp	31.6 kWp	Number of PV modules	452 units
Max. voltage (V_{mpp})	671 V	596 V	Nominal (STC)	244 kWp
Max. current (I_{mpp})	119 A	53 A	Total Area	1166 m^2
Part	**Inverter array characteristics**		**Inverter specifications**	
	Array1 Array3	**Array2 Array 4**	**Manufacturer**	**SMA**
Number of inverters	9 * MPPT 8% 0.7 unit	3 * MPPT 9% 0.3 unit	Model	Sunny Tripower STP110-60-Core2
Total power	78.8 kWac	31.2 kWac	Unit Nom. Power	110 kWac
Operating voltage	200-800 V	200-800 V	Number of inverters	2 units
Pnom ratio (DC:AC)	1.11	1.11	Total power	220 ac

According to Fig. 5, The photovoltaic mechanism of Arab African International Bank is strategically placed on the rooftop of the bank's building. The location was carefully chosen to maximize the system's efficiency and effectiveness in harnessing solar energy. With a module tilt of 0° for Exploiting the largest area of the surface to ensure the administrative capital for urban development (ACUD) requirements that 50% of the roof area is filled with solar cells, the PV system is optimally positioned to receive maximum sunlight throughout the day. The rooftop placement not only utilizes the available space efficiently but also ensures minimal obstruction from surrounding structures, allowing the panels to capture sunlight at its highest potential. This arrangement displays the bank's commitment to sustainable energy practices and reinforces its dedication to reducing its carbon footprint.

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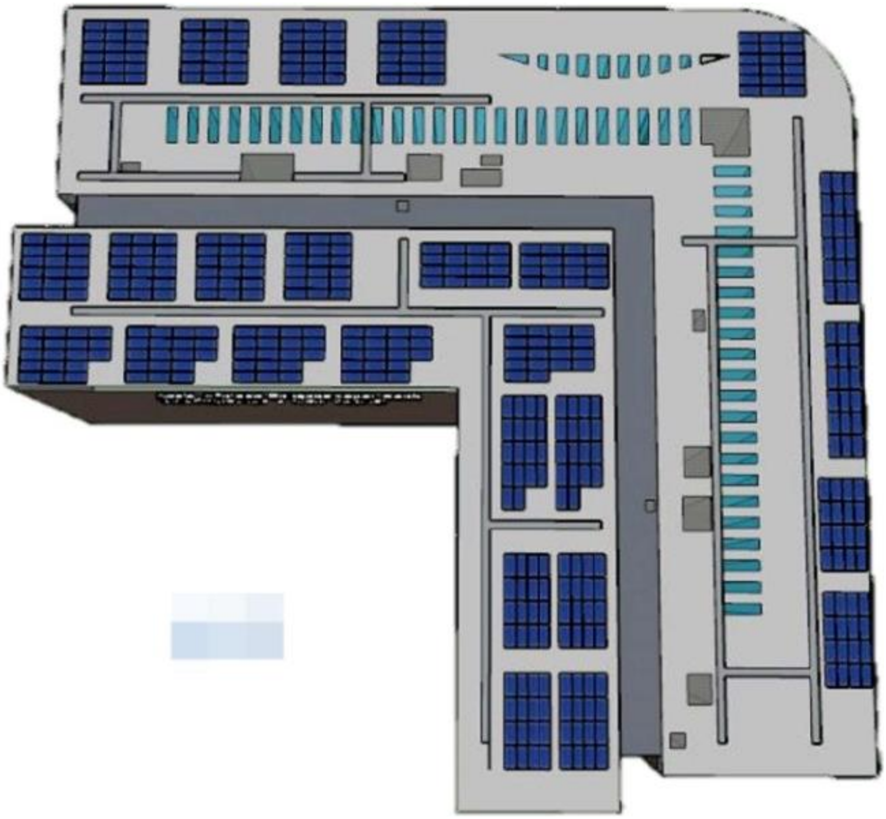

Fig. 5. PV system arrangement location on the building rooftop

When performing a lightning risk assessment and designing lightning protection systems for photovoltaic (PV) installations, it is crucial to recognize and address any limitations and assumptions. This ensures a balanced view and prepares stakeholders for potential deviations or uncertainties. Below are key considerations:

Limitations:

1. Data Accuracy and Completeness:
    - Lightning Data: The risk assessment relies on historical lightning strike data, which may vary in accuracy and coverage. Regional variations and gaps in historical records can affect the precision of the lightning risk assessment.
    - Weather Patterns: Predictions based on historical weather patterns may not fully account for recent changes or extreme weather events, impacting the accuracy of lightning risk evaluations.
2. System Constraints:
    - Design Limitations: Physical and structural constraints of the installation site, such as limited space or architectural features, may affect the placement and effectiveness of lightning protection components.
    - Integration Challenges: Integrating lightning protection systems with existing PV infrastructure may present challenges that can influence the design and overall effectiveness of the protection measures.
3. Technological Limitations:
    - Protection Devices: Surge protection devices (SPDs) and other lightning protection components have limitations in terms of their capacity and response time. These limitations may affect their ability to fully protect the PV system from high-energy lightning strikes.

- Detection and Monitoring: Real-time lightning detection and monitoring systems may have limitations in accuracy, coverage, or reliability, impacting the effectiveness of early warning and response measures.

4. Environmental and Climatic Factors:
   - Variable Conditions: Environmental factors such as soil conductivity, moisture levels, and local weather conditions can affect the performance of grounding systems and lightning protection measures.
   - Maintenance Issues: Environmental conditions like dust, pollution, or corrosion can impact the longevity and effectiveness of lightning protection components, potentially leading to reduced performance over time.
5. Regulatory and Code Compliance:
   - Standards Variability: Different regions may have varying codes and standards for lightning protection. Compliance with local regulations may not always align with international best practices, potentially affecting the overall design and effectiveness.

Assumptions

1. Lightning Strike Frequency:
   - Average Risk: The assessment often assumes an average frequency of lightning strikes based on historical data. This may not account for local variations or recent changes in lightning activity.
2. Component Performance:
   - Standard Efficiency: It is assumed that lightning protection components, such as lightning rods, down conductors, and SPDs, will perform according to their specifications and in line with industry standards. Real-world performance may vary due to manufacturing differences or installation issues.
3. Installation Quality:
   - Adherence to Standards: The design assumes that all lightning protection measures will be installed correctly and maintained according to best practices. Deviations from these standards can impact the effectiveness of the protection system.
4. Grounding Effectiveness:
   - Soil Conductivity: The effectiveness of grounding systems is assumed based on average soil conductivity values. Variations in soil properties, such as high resistivity or heterogeneous composition, can affect grounding performance.
5. Static Risk Profile:
   - Constant Risk Levels: The risk assessment may assume that the lightning risk profile remains constant over time. Changes in building use, structural modifications, or environmental conditions can alter risk levels.
6. Technological Advancements:
   - Current Technology: The design is based on the current state of technology for lightning protection. Future advancements may provide new solutions or improve existing technologies, potentially impacting the effectiveness of current designs.

By acknowledging these limitations and assumptions, stakeholders can better understand the potential uncertainties and risks associated with lightning protection design for PV systems. This awareness facilitates more informed decision-making and preparation for deviations from expected outcomes.

In conclusion, the lightning risk assessment for photovoltaic (PV) systems underscores the critical importance of integrating robust lightning protection measures to ensure the safety, reliability, and efficiency of solar energy installations. By acknowledging the limitations and assumptions inherent in the risk assessment process—such as variations in lightning data, installation constraints, and technological limitations—designers and operators can better prepare for potential deviations and uncertainties. Effective lightning protection, including the strategic placement of lightning rods, surge protection devices, and grounding systems, is essential to mitigate the risk of damage from lightning strikes. Implementing these measures not only safeguards the PV system against electrical surges and potential fires but also contributes to the long-term stability and performance of the installation. A well-designed lightning protection strategy is vital for protecting valuable infrastructure, reducing maintenance costs, and maximizing the return on investment in solar energy technology.

4.1. Risk Estimated as per IEC 62305-2

4.1.1. The lightning Ground Flash Density (N_g)

The amount of lightning strikes on Earth per square kilometre during a given year is known as the "flash density," and the higher the number, the more frequent lightning strikes occur [35]-[38].

The unit of measurement for Ng is flashes/km²/year. This unit helps in quantifying how common lightning events are in a particular geographic location. It is an important parameter in understanding and managing lightning risks, particularly in the design and installation of lightning protection systems for buildings and infrastructure. modern lightning detection networks, such as those using satellite and ground-based sensors, provide accurate data on lightning flash density. Lightning ground flash density varies significantly by geographic region, with tropical and equatorial areas experiencing higher Ng due to more frequent thunderstorms compared to temperate or polar regions.

Ng is a crucial metric for understanding the frequency of lightning strikes in each area. It plays a key role in risk management, safety planning, and the design of lightning protection systems.

Importance:

- Design Considerations: Ng is crucial for designing and implementing effective lightning protection systems. Areas with high Ng values require more robust protection measures due to the increased frequency of lightning events.
- Risk Assessment: Understanding the lightning ground flash density helps in assessing the risk of lightning strikes to buildings, infrastructure, and other critical systems. It informs decisions on where to place lightning rods and other protective measures.
- Insurance and Safety: Knowledge of Ng can influence insurance policies and safety protocols by providing data on the potential risk and likelihood of lightning-related damage.

It can be calculated as follows:

$$N_g = 0.1T_d \tag{10}$$

Where T_d refers to the annual number of days with thunderstorms.

Number of Thunderstorm Days refers to the count of days in a specific period, usually a year during which thunderstorms occur in a particular region. This metric is important for understanding regional weather patterns, assessing lightning risks, and planning for weather-related impacts. The number of thunderstorm days is the count of days on which thunderstorms are recorded. Thunderstorms can vary in intensity, but any day with at least one thunderstorm event counts as a thunderstorm day. meteorological stations and weather monitoring systems track the occurrence of thunderstorms. These systems record the frequency and duration of thunderstorm events. The number of thunderstorm days is typically reported annually and can vary by region. It is often used in weather summaries and climate reports. Understanding the number of thunderstorm days helps in analyzing regional weather patterns and seasonal variations. It provides insight into the frequency and distribution of thunderstorms in different areas. High numbers of thunderstorm days indicate increased risk of severe weather events, including lightning strikes, hail, and strong winds. This information is vital for planning infrastructure, emergency preparedness, and safety measures. The number of thunderstorm days varies widely by geographic location. Regions with warm, humid climates, such as tropical and subtropical areas, typically experience more thunderstorm days compared to cooler, drier regions.

4.1.2. Area of Structure to be Protected

It can be evaluated for rectangular structure as the following:

$$A_d = (L \times W) + 6H(L \times W) + 9\pi H^2 \tag{11}$$

which stand for the length, width, and height, respectively, L, W, and H. related to building that needs protection, respectively, measured in meters.

4.1.3. The Structure's Relative Location

This factor, C_d considers the association of the surrounding structures.

4.1.4. Number of Dangerous Events within a Structure (N_D)

$$N_D = N_g A_d C_d \times 10^{-6} \tag{12}$$

Ng, which is expressed in terms of 1/km2year, is the lightning flash density of the ground A_d The structure's collection area and is measured in (m^2). C_d is a factor related to the structure's location.

4.1.5. The Average Number of Hazardous Incidents Caused by Lightning Strikes Close to a Structure Each Year (Nm)

$$N_m = N_g A_M 10^{-6} \tag{13}$$

Where, Ng, which is expressed in terms of 1/km2year, is the lightning flash density of the ground. A_M represents the area where lightning strikes occur close to the building structure, measured in (m^2). The A_M accumulation area reaches up to 500 m from the structure's perimeter.

$$A_M = 1000(L + W) + 250000\pi \tag{14}$$

4.1.6. The Count of Hazardous Incidents (N_{DJ}) Pertaining to a Nearby Structure

$$N_{DJ} = N_g A_{DJ} C_{DJ} C_T \times 10^{-6} \tag{15}$$

Where A_{DJ} is related to the adjacent structure collection area (m^2). C_{DJ} is a factor related to the adjacent structure's location. C_T is related to the factor of the service line type.

4.1.7. The Quantity of Hazardous Incidents Resulting from Occurrences of Flashes to a Service Line

The line can be composed of multiple parts. Through each part of the line, N_L value is conducted by:

$$N_L = N_g A_L C_I C_E C_T \times 10^{-6} \tag{16}$$

Where NL is the line's overvoltage of amplitude that is not less than 1 kV (1/year). A_L is the collection of accumulation area where the line is stroked by lightning flash (m^2). C_I is the line's factor of installation. C_T is the factor for the type of line. C_E is the factor related to the surrounding environment. among the strikes to the line within the collection area:

$$A_L = 40 L_L \tag{17}$$

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The length of the line segment (m) is represented by L_L. When a line section's length is unknown, LL = 1000 m should be presumed.

4.1.8. The Quantity Subject to Hazardous Incidents Caused by Flashing Near a Service Line

A line can be made up of multiple sections. For every line section, $_I$ value may be calculated. through the following calculation:

$$N_I = N_g A_I C_I C_E C_T \times 10^{-6} \tag{18}$$

N_I represents the line section's overvoltage of amplitude not less than 1 kV (1/year). with the collection area for flashes near a line.

$$A_I = 4000 L_L \tag{19}$$

When a line section's length is unknown, L_L = 1000 m should be presumed.

4.1.9. Probability PA that an Electric Shock from a Flash to a Building will Injure Organisms

1. Probability (P_{TA}): The value of probability that a strike to a structure object will cause harm to organisms due to contact and step voltage by a flash to the structure due to lightning [39].
2. Probability (P_B): The probability that physical harm will result from a flash to a building structure, it depends on the lightning protection level (LPL) [40].

$$P_A = P_{TA} P_B \tag{20}$$

4.1.10. Probability PC that Causes Malfunction of the Inner Systems Resulting from Strike to a Structure

The probability that causes malfunction of the inner systems resulting from a strike to a structure based on the coordinated SPD protection that has been adopted. The lightning protection level for which SPD is designed determines the values of P_{SPD}.

$$P_C = P_{SPD} C_{LD} \tag{21}$$

4.1.11. Probability PM that a Flash Near a Structure Resulting in the Malfunction of Internal Systems

Probability (P_M): The probability PM of internal system failure resulting from a lightning strike near a structure is contingent upon the lightning protection measures (LPM) in place. If a coordinated SPD system that meets the requirements of IEC 62305-4 is not available, then the value of P_M will be the same as the value of P_{MS}.

The equation below gives the value of P_M when a coordinated SPD system based on IEC 62305-4 is implemented.

$$P_M = P_{SPD} P_{MS} \tag{22}$$

$$P_{MS} = (K_{S1} K_{S2} K_{S3} K_{S4})^2 \tag{23}$$

Where:

$$K_{S1} = 0.12 W_{m1} \tag{24}$$

$$K_{S2} = 0.12 W_{m2} \tag{25}$$

The distance between the structure's metal columns can be indicated asW_{m1} (m) and W_{m2} (m). K_{S3} related to the property's consideration of the inner wiring. K_{S4} for the structure object to be protected, consider the withstand voltage of impulse. For inner systems using equipment that does not conform to the resistibility or withstand voltage ranges specified in the appropriate product standards, P_M=1 should be presumed.

For (KS_4) is evaluated as:

$$K_{S4} = \frac{1}{U_W} \tag{26}$$

Where, U_w: for the system that required protection, consider the impulse of withstand voltage, in kV.

4.1.12. Probability PU that Harm to People Caused by Shock of Electricity in Case of a Strike to the Service Line

$$P_U = P_{TU} P_{EB} P_{LD} C_{LD} \tag{27}$$

Where, P_{TU} the effectiveness of touch voltage protection measures relies on factors such as implementing physical barriers or providing warning notices. P_{LD}: is the probability of the malfunction related to the inner system by a strike on the associated network line dependent on-line properties. P_{EB} is dependent upon the equipotential bonding of lightning as per IEC 62305-3 and the level of lightning protection that is why its surge protective devices are established for designing is a factor related to the line properties which is dependent upon the isolation conditions, grounding and shielding [41]-[43].

4.1.13. Probability P_V that a Strike to the Line Network will Result in Physical Harm

$$P_V = P_{EB} P_{LD} C_{LD} \tag{28}$$

4.1.14. Probability P_W that a Flash to the line Network will Result in a Malfunction of the Inner Systems which is Given by

$$P_W = P_{SPD} P_{LD} C_{LD} \tag{29}$$

Where P_{SPD} relies on the level of protection system of lightning. P_{LD} represents the probability of malfunction of the inner mechanism of the system resulting in a strike to the line dependent upon the properties of the associated line network.

4.1.15. Probability P_Z that a Lightning Strike Close to an Incoming Service Network Line will Result in a Malfunction of the Inner Systems Mechanism. which is Given by:

$$P_Z = P_{SPD} P_{LI} C_{LI} \tag{30}$$

Where P_{LI} is the probability of malfunction of the inner mechanism of the associated system resulting in a strike close to the line connected to the service network dependent upon the properties of the connected line and equipment. C_{LI} is a factor related to the service line grounding, isolation status and the shielding of the line.

The relation between the probabilities of damage failure and lightning flash density is that as the lightning flash density increases, the probability of damage failure also tends to increase. This is because higher lightning flash densities indicate a greater likelihood of lightning strikes occurring, which in turn increases the risk of damage to buildings, infrastructure, and electronic equipment. Therefore, areas with higher lightning flash densities are associated with higher probabilities of damage failure.

4.1.16. Amount of Mean Relative Loss per Risky Event

1. Loss of human life

Where L_T stands for the average relative number of electric shock victims injured in a single, risky incident. The average relative numbers of victims who suffer failure damage and physical harm,

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respectively, in a single risky occurrence are denoted by L_F and L_O. It is a factor that, depending on the kind of floor or soil, reduces the loss of human life. r_P is a factor Depending on the efforts made to mitigate the fire impact. lowers the loss brought on by physical damage. r_f is a factor that, subject to the possibility of an explosion inside the building structure, reduces any loss brought on by physical harm. When a particular risk exists, h_z is a factor that raises any loss caused by physical harm. The total number of individuals living in the zone is represented by n_z, while the overall number of persons in the structure itself is represented by n_t. The annual duration time in hours that people spend in the zone is expressed as t_z. The value of loss per zone shown in Table 6.

Table 6. The value of loss per zone

Different Forms of Harm Damage	Commonly Encountered Losses	
D_1	$L_A = r_t L_T \left(\frac{n_z}{n_t}\right)\left(\frac{t_z}{8760}\right)$	(31)
D_2	$L_B = L_V = r_P r_f h_z L_F \left(\frac{n_z}{n_t}\right)\left(\frac{t_z}{8760}\right)$	(32)
D_3	$L_C = L_M = L_W = L_Z = L_O \left(\frac{n_z}{n_t}\right)\left(\frac{t_z}{8760}\right)$	(33)

2. Loss related to service to the public

The value of loss per zone shown in Table 7.

Table 7. The value of loss per zone

Different forms of harm damage	Commonly encountered losses	
D_2	$L_B = L_V = r_P r_f L_F \left(\frac{n_z}{n_t}\right)$	(34)
D_3	$L_C = L_M = L_W = L_Z = L_O \left(\frac{n_z}{n_t}\right)$	(35)

4.2. Risk Components (R_A, R_B, R_C)

1. Harm to living beings (R_A): -

$$R_A = N_D P_A L_A \tag{36}$$

2. Physical harm to a structure (R_B):

$$R_B = N_D P_B L_B \tag{37}$$

3. Risk component (failure of internal system) (R_c):

$$R_A = N_D P_C L_C \tag{38}$$

4.3. Risk Components (R_U, R_V, R_W, R_Z)

1. Evaluation of the danger factors generated by an unexpected strike to a structure-connected line. (S_3)

- Component associated with electric shock injuries to living beings (D_1)

$$R_U = (N_L + N_{DJ}) P_U L_U \tag{39}$$

- Component subject to physical damage (D_2)

$$R_V = (N_L + N_{DJ}) P_V L_V \tag{40}$$

- Component subject to the internal systems failure (D_3)

$$R_W = (N_L + N_{DJ})P_W L_W \tag{41}$$

2. Evaluation of the risk components caused by sudden strike close to a structure-connected line (S_4)

- Component related to the internal systems malfunction (D_3)

$$R_Z = N_I P_Z L_Z \tag{42}$$

3. Composition of risk components

- Risk to life of humans. (R_1)

$$R_1 = R_A + R_B + R_C{}^* + R_M{}^* + R_U + R_V + R_W{}^* + R_Z{}^* \tag{43}$$

- Risk of services to the public disruption. (R_2)

$$R_2 = R_B + R_C + R_M + R_V + R_W + R_Z \tag{44}$$

- Risk of loss of heritage of cultural (R_3)

$$R_3 = R_B + R_C \tag{45}$$

- Risk of losing economical value. (R_4)

$$R_4 = R_A{}^* + R_B + R_C + R_M + R_U{}^* + R_V + R_W + R_Z \tag{46}$$

R^*) Specifically for properties in which there is a risk of animals' loss [31].

5. Study Case Calculations (As per Project Condition all Values Selected from the Standard Tables)

5.1. Structure Dimensions and Area

Table 8 contains the structure length, width, and height. Moreover, obtaining collection area (Am and Ad) [31].

Table 8. Area and dimensions of structure

Length	98.5 m
Width	94 m
Height	38.5 m
Collection Area (A_d)	95636.1 m^2
Collection Area (A_m)	977898 m^2

5.2. Collections Area of Lines (Power and Telecommunication)

Table 9 contains the length of the power line. Moreover, obtaining the collection area (A_L, A_I) [31].

Table 9. Collection area of power line

Length of power line	1000 m
Collection Area (A_L)	40000 m^2
Collection Area (A_I)	$4x10^{+06}$ m^2

5.3. Structure's Attributes

Table 10 contains reduction factor (r_f), mesh widths (w_{m1}, w_{m2}), considered the screening effectiveness of the structure (K_{S1}) and of shields internal to the structure (K_{S2}) Also, considered the properties of inner wiring (K_S) [31].

Table 10. Structure's attributes

Reduction factor (r_f)	Fire – Low	0.001
w_{m1}	8.4m	meter
w_{m2}	8.4m	meter
K_{S1}	1.008	
K_{S2}	1.008	
K_{S3}	Shielded and running cables in metal conduits	0.0001

5.4. Environmental Influences

Table 11 contains the line environmental factor (C_E), The total number of thunderstorms days yearly (T_d) and Lightning flash density on the ground (N_g) [31].

Table 11. Environmental influences

Line environmental factor C_E	**Urban**	**0.1**
The factor location C_D	Structure bordered by objects of equal or smaller height	0.5
T_d	10	days/year
N_g	1	flashes/km^2/year

5.5. Service Lines

Table 12 contains the line routing, shielding and bonding conditions. Also, the line factor of installation (C_I), (C_T) is a factor related to the line type, the withstand voltage (U_W), factors depending on the isolation status of the line, the shielding related to the line and the line grounding. (C_{LI}, C_{LD}) and the probability that a strike to an incoming line will result in harm to living beings (P_{TU}) [31].

Table 12. Service lines

Select Routing, shielding and bonding conditions	Shielded aerial or buried whose shield bonded to the same bonding bar as equipment & 1W/km < R_S ≤5 W/km	
Line installation factor C_I	Buried	0.5
Line type factor C_T	HV power (with HV/LV transformer)	0.2
U_W	1	kV
Factor C_{LI}	Lightning protective cable or wiring in lightning protective cable ducts, metallic conduit, or metallic tubes - Connection at the entrance: Shield bonded to the same bonding bar as equipment.	0
probability P_{TU}	Physical restrictions	0
Factor C_{LD}	Lightning protective cable or wiring in lightning protective cable ducts, metallic conduit, or metallic tubes - Connection at the entrance: Shield bonded to the same bonding bar as equipment.	0

5.6. Protection Measures

Table 13 contains the additional protection measures (P_{TA}), the probability that a strike to a structure will result in physical harm (P_B), and the probability depending on the SPD system and lightning level protection (P_{SPD}), reduction factors (r_p,rt) and the probability (P_{EB}) depending on the equipotential bonding [31].

Table 13. Protection measures

Additional Protection Measure (P_{TA})	Physical restrictions or building framework used as a down-conductor system.	0
Probability (P_B)	Structure protected by LPS - Class of LPS IV	0.2
Probability (P_{SPD})	III-IV	0.05
Reduction factor (r_p)	One of the following provisions: fixed automatically operated extinguishing installations; automatic alarm installations.	0.2
Reduction factor (r_t)	Marble, ceramic	0.001
Probability (P_{EB})	III-IV	0.05

5.7. Loss of Human Life (L_1)

Table 14 contains factors representing the increasing loss by physical harm **(h_z),** the typical mean relative numbers of victims injured by electric shock **(L_T),** the typical mean relative numbers of victims by physical and malfunction damage (L_F, L_O), the number of individuals in the zone. (n_z), the Total quantity of individuals in the structure. (n_t), and the amount of time in hours annually that the individuals spend in the zone. (t_z) [31].

Table 14. Loss of human life

Factor (h_z)	Low level of panic	2
L_T	All types of structure	0.01
L_F (Loss L_1)	Industrial, Commercial	0.02
L_O (Loss L_1)	Other parts of the hospital	0.001
Number (n_z)	100	
Number (n_t)	50	
Time (t_z)	2400	hours per year

5.8. Public Service Loss (L_2)

Table 15 contains the victim's numbers by physical and failure harm (L_F, LO) [31].

Table 15. Public service loss

L_F (L_2 Loss)	Gas, water, power supply	0.1
L_O (L_2 Loss)	TV, telecommunications lines	0.001

6. Results and Discussions (all Obtained Values are Discussed in Last Paragraphs)

6.1. Annual Dangerous Events number

Table 16 the total count of hazardous incidents associated with a particular structure (N_D), the Mean quantity of risky incidents caused by strikes of lightning in close proximity to a structure each year (N_m), The quantity of hazardous incidents due to strokes to a utility line (N_L) and the quantity of hazardous incidents due to strokes near to the service line (N_I) [31].

Table 16. Yearly number of dangerous incidents

N_D	4.78181×10^{-02}
N_M	9.77898×10^{-01}
N_L	4.00000×10^{-04}
N_I	4.00000×10^{-02}

6.2. Human Life Loss (L_1)

Table 17 obtains the loss due to harm to living beings resulting in shock of electricity (L_A, L_U), physical harm loss (L_B, L_V), and inner systems malfunction loss (L_C, L_M, L_W, L_Z) [31].

Table 17. Loss of human life

L_A	5.47945×10^{-06}
L_U	5.47945×10^{-06}
L_B	4.38356×10^{-06}
L_V	4.38356×10^{-06}
L_C	5.47945×10^{-04}
L_M	5.47945×10^{-04}
L_W	5.47945×10^{-04}
L_Z	5.47945×10^{-04}

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The value for loss of human life is a critical element in lightning risk assessment for PV systems. It influences the overall risk evaluation by emphasizing the need for stringent safety measures and effective protection strategies. By integrating this value into the risk assessment, designers and operators can prioritize human safety, ensure compliance with safety standards, and implement comprehensive protection measures. This approach not only safeguards individuals but also enhances the overall resilience and reliability of PV systems against lightning-related hazards.

6.3. Risk Components for R_1

Table 18 obtains the risk parts (physical harm to a structure) (R_B) and the Risk component corresponds to the internal system failure (R_M) [31].

Table 18. Risk component for R1

R_B	4.19227 x10^{-08}
R_M	2.76594 x10^{-13}

6.4. Probability of Damage to Structure

Table 19 obtains the probability that a strike to the structure object results in physical harm (P_B), the probability that a strike close to a structure result in malfunction of the inner system mechanism (P_M), the probability that a flash connected to the line cause a failure of internal system (P_{LD}), the probability that a strike close to the connected line result in malfunction of the inner system (P_{LI}) and If a SPD system that confirms what is needed of IEC 62305-4 is not available, then (P_M) value will be the same as (P_{MS}) value [31].

Table 19. Probability of damage to structure

P_B	2.00000 x10^{-01}
P_{MS}	1.03239 x10^{-08}
P_M	5.16193 x10^{-10}
P_{LD}	9.00000 x10^{-01}
P_{LI}	1.00000 x10^{-00}

6.5. Public Service Loss (L_2)

Table 20 shows the physical harm loss (L_B, LV) and the inner system malfunction loss (L_C, L_M, L_W, L_Z) [31].

Public Service Loss (L_2) is a critical factor in lightning risk assessment for PV systems due to its potential impact on essential services and infrastructure. It affects the overall risk profile by highlighting the broader implications of service disruptions on the community. The adequacy of protection measures must be evaluated considering this risk, ensuring that lightning protection strategies are comprehensive and robust. Effective lightning rods, SPDs, improved grounding systems, redundancy, and contingency planning are essential to mitigating this risk and ensuring the continued reliability and resilience of PV systems and the public services they support.

Table 20. Public service loss (L_2)

L_B	*4.00000* x10^{-05}
L_V	4.00000 x10^{-05}
L_C	2.00000 x10^{-05}
L_M	*2.00000* x10^{-05}
L_W	2.00000 x10^{-05}
L_Z	2.00000 x10^{-05}

6.6. Risk Components for R_2

Table 21 shows that the risky component results in physical damage to a structure object (R_B) and the risky component corresponds to the internal system failure (R_M) [31]. After applying the risk assessment, the obtained results are R_1= 4.19230 x10^{-08} and R_2=3.82546 x10^{-07}. The risk analysis calculation for the study case depends on various factors as explained before in the detailed methodology based on IEC 62305-2 [44]-[48]. Which contains many tables and equations subject to a lot of cases of various structures to be protected [49], [50]. The calculation starts with the input data of the structure as the area, the structure attributes, the environmental influence, the lines of service, measures of protection, human life loss (L_1) and public service loss. Then, the obtained sub-result leads to obtaining the calculated risk, which is the sum of its risk parts. The obtained result is R_1 (risk of human life loss) and R_2 (risk of public service loss) compared to the tolerable R_T ($R_1 < 10^{-5}$ & $R_2<10^{-2}$). Then, the calculated risk is lower than the tolérable risk which means that level ɪv of protection is suitable for the structure. Therefore, the concept design is subject to level ɪv for all related parameters such as the separation distance between the down conductor and the size of the mesh, etc. Then, accurate risk analysis leads to accurate lightning design. When the calculated lightning risk exceeds tolerable levels, taking comprehensive action to enhance lightning protection is essential. Upgrading components such as lightning rods, down conductors, and grounding systems, as well as improving system design and implementing robust maintenance practices, can significantly reduce the risk to acceptable levels. By addressing these areas, designers and operators can ensure the PV system is well-protected against lightning strikes, enhancing its safety, reliability, and overall performance. Future research in Lightning risk assessment for PV systems is crucial for advancing the effectiveness and resilience of solar energy infrastructure. By focusing on advanced risk prediction models, innovative protection technologies, integration with system design, and the impact of environmental factors, researchers can contribute to more robust and reliable PV systems. Addressing these research areas will enhance our ability to gère lightning risks and ensure the continued growth and success of solar energy technology. For this case related to future research it is recommended to focus on the wind system or the hyprid system to make similar study.

Table 21. Risk components for R_2

R_B	3.82545×10^{-07}
R_M	1.00957×10^{-12}

7. Conclusions

It is crucial to perform a risk assessment according to the international standard 62305 and carefully lightning protection systems to effectively appropriate safeguards against external surges. Ensuring the safe operation of PV installations, which are significant capital investments, is imperative and can be accomplished by designing and implementing a dependable LPS. To guarantee the protection of PV modules analyzing. Also, comprehending the impact of lightning on them is essential. Specifically, understanding the lightning-induced voltage on a photovoltaic system and its properties enables Researchers to take specific precautions during the design of the PV to protect it.

The evaluation of measures related to lightning protection on the photovoltaic systems should based on all analysis of risks and the associated costs of protection. in this paper, the calculated risk is obtained by applying the steps of risk management from the series of IEC 62305 to the structure mechanism. The calculation of the risk analysis leads to the result of obtaining the calculated risk. Then, obtain the protection design of lightning which is subject to the protection level based on the criteria and formulas from the IEC 62305 standard. Risk assessment is crucial for identifying potential hazards and vulnerabilities in photovoltaic (PV) systems, particularly regarding lightning strikes. It enables the evaluation of potential impacts on both equipment and human safety, guiding the implementation of effective mitigation strategies. A reliable lightning protection system (LPS) is essential to safeguard PV installations from lightning-induced damage, ensuring system integrity and operational continuity. By effectively intercepting, conducting, and dissipating lightning energy, an LPS prevents costly repairs, service disruptions, and safety risks, thereby maintaining the reliability and efficiency of solar energy systems.

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