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Risk assessment, lightning protection, and earthing system design for photovoltaic power plants: A case study of utility-scale solar farm in Iran

Mohammad Parhamfar [a], Reza Naderi [b], Iman Sadeghkhani [a,c,*]

[a] Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad 85141-43131, Iran
[b] Rahnama Tejart Pasargad Company, Tehran 14316-54384, Iran
[c] Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad 85141-43131, Iran

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ABSTRACT

Photovoltaic (PV) systems play a pivotal role in addressing the growing global demand for sustainable and renewable energy sources, offering a crucial solution to mitigate climate change and reduce dependence on fossil fuels. Due to outdoor installation, PV systems are vulnerable to lightning strikes, which can cause significant damage to the electrical system and pose a safety hazard. Therefore, effective lightning protection measures including the use of surge protective devices, lightning rods, earthing systems, and shielding techniques are crucial to ensure the reliable and safe operation of PV systems. However, the design and implementation of lightning protection system (LPS) continue to be a complex and challenging task for engineers. This paper presents the step-by-step design of an LPS for a large-scale PV power plant located in Iran based on IEC 62305:2010. The procedure includes various aspects of lightning protection including risk assessment, earthing system, and bonding according to the relevant international standards and guidelines. The results show that the non-isolated passive LPS and galvanized earthing system are proper choices for the PV power plant under study. The findings of this paper are of interest to PV system designers, installers, operators, and researchers, as well as to standards organizations, regulatory bodies, and insurance companies involved in the certification and evaluation of PV systems.

1. Introduction

Renewable power capacity is set to grow steadily over the next five years until 2028, with solar photovoltaic (PV) and wind projected to account for a record-breaking 96% of new additions [1]. This dominance is driven by their lower generation costs compared to both fossil and other non-fossil fuel sources in most countries, as well as strong policy support. In 2022, solar PV generation surged by a record 270 TWh (up 26%), reaching nearly 1,300 TWh. This marked the largest annual increase in renewable generation [2–6] and, for the first time, exceeded that of wind. It is expected to lead future investments, as solar PV has become the lowest-cost option for new electricity generation in most parts of the world. This growth rate aligns with the Net Zero Emissions by 2050 Scenario projections for 2023–2030. The economic appeal of PV, rapid supply chain expansion, and growing policy support, especially in China, the United States, the European Union, and India, are expected to further accelerate capacity growth in the years ahead.

Lack of greenhouse gas emissions, unlimited primary energy source, accessibility, low maintenance requirements, ability to operate in various scales from rooftop household systems to large power plants, advancements in solar panel technology, and government subsidies are other reasons for paying attention to the PV systems [7–13]. In Iran, due to the development of renewable energy resources over the past decade and international commitments to reducing greenhouse gas emissions, followed by the government's plans to develop this industry, the country has also witnessed the development of various types of renewable power plants in recent years. Given the conditions of solar radiation and having more than 330 sunny days in most parts of Iran, PV power systems have had the most development in this country. Iran's capacity for installing renewable power plants has reached 1 GW, of which 420 MW is from solar energy [14]. However, the further development of PV systems requires addressing the upcoming challenges, especially their protection system.

Due to outdoor installation, PV systems are exposed to various environmental hazards, including lightning strikes, which can cause significant damage to the system's components, leading to costly repairs, downtime, and safety hazards. Damages to electrical installations are caused by direct lightning strikes or induced overvoltages (indirect strikes). Electric discharges caused by lightning sometimes reach

* Corresponding author at: Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad 85141-43131, Iran.
E-mail address: sadeghkhani@pel.iaun.ac.ir (I. Sadeghkhani).

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Nomenclature

Symbols

a_s	Distance between sun and earth (m)
d_f	Lightning rod/line diameter (m)
d_s	Sun diameter at the equator (m)
h_e	Maximum height of the equipment (m)
h_r	Rod height (m)
k_c	coefficient of the number of down conductors
k_i	Protection level factor
k_m	Insulation coefficient of the material
l	Distance from the point where the separation distance is measured to the nearest bonding point for equipotentialization (m)
L_x	Consequent loss
N_x	Number of dangerous events (Year^{-1})
P_x	Probability of structure damage
R	Overall risk (Year^{-1})
r_p	Protective radius (m)
r_s	Rolling sphere radius (m)
R_T	Tolerable risk (Year^{-1})
R_x	Risk components (Year^{-1})
$R1$	Risk of human life loss (Year^{-1})
$R2$	Risk of public service loss (Year^{-1})
$R3$	Risk of cultural heritage loss (Year^{-1})
$R4$	Risk of economic value loss (Year^{-1})
R_A	Refers to the injury to living beings caused by step and touch voltages in the event of a direct strike
R_B	Refers to physical damage caused by sparking inside the structure that triggers an explosion or fire in the event of a direct strike
R_C	Refers to the failure of the internal system due to lightning electromagnetic impulse (LEMP) in the event of a direct strike
R_M	Refers to the failure of the internal system due to LEMP in the event of an indirect strike
R_U	Refers to injury to living beings caused by step and touch voltages in the event of a lightning strike on a line connected to the structure
R_V	Refers to physical damage caused by sparking between metallic parts and external installations due to transmitted lightning current through incoming services in the event of a lightning strike on a line connected to the structure
R_W	Refers to the failure of internal systems due to induced overvoltage on incoming lines transmitted to the structure in the event of a lightning strike on a line connected to the structure
R_Z	Refers to the failure of internal systems due to induced overvoltage on incoming lines transmitted to the structure in the event of a strike near a line connected to the structure
s	Safety distance (m)

Abbreviations

ATS	Air-termination system
CSA	Cross-sectional area (mm^2)
GPR	Ground potential rise
IEA	International energy agency
LPS	Lightning protection system
LV	Low voltage
MV	Medium voltage
PV	Photovoltaic
SD	Separation distance (m)
SPD	Surge protective device

several hundreds of kiloamperes and cause field-based and directed electrical interferences. These interferences increase with the increase in the length of the cables or conductor loops. Surge waves not only damage PV power modules, inverters, and their electronic monitoring equipment but also lead to damage to equipment in building facilities. Most importantly, the power generation equipment of commercial buildings may also be easily damaged. If surge waves are injected into systems that are far from the main grid (off-grid PV systems), the operation of equipment that is powered by the PV system (such as medical equipment and water supplies) is disrupted. Despite the technical advances, no equipment can prevent the occurrence of lightning. Therefore, an effective protection system against lightning and transient overvoltages is one of the basic requirements of PV power systems to significantly increase their efficiency and reduce maintenance time and spare parts cost.

Lightning protection systems (LPSs) consist of external (air-terminal), lightning conductors, and earthing electrodes and internal (protective measures to reduce the electromagnetic effects of the lightning current entering the protected structure) protection systems to minimize damage to the equipment. In the design of an LPS, protection against lightning strikes (creating a safe lightning strike point for lightning strikes), connecting the lightning current to the ground, discharge of lightning current in the ground, and equipment equipotentialization to prevent the risk of the voltage difference between LPS, structure, and devices/circuits inside the structure should be considered. The protection engineer should design a protection system at the set risk limit or less by selecting protective equipment in a suitable protection class. Also, these protective measures can be implemented: (i) insulation of parts without conductive coating to reduce the risks of contact and step voltages, (ii) creating physical restrictions for access to LPS equipment and installing warning signs, and (iii) use of fire extinguishing systems, use of fireproof equipment and safe emergency exit routes to prevent physical damage.

Ref. [15] investigates the eddy current inside a PV module caused by lightning electromagnetic field. The effect of earthing resistance of the grid on the variation of transient grounding potential rise and induced overvoltage resulting from indirect lightning stroke is discussed in [16] for a 1 MW PV plant. In [17], the transient behavior of the PV system models is investigated when struck by lightning. Ref. [18] proposes a cable wiring scheme for the DC section of PV systems to mitigate the lightning-induced overvoltage. The calculation of induced overvoltages on DC cables of the PV system is presented in [19], where the DC cable arrangement modification and impact of concrete foundation presence in the earthing system are also investigated. The performance of the earthing system of a PV system equipped with independent lightning rods during lightning is investigated in [20]. Ref. [21] presents the modeling and LPS design guidelines for a PV string. In [22], the performance of the LPS of a PV park is investigated and the earthing system is designed. The lightning performance and surge failures of a PV system are investigated in [23].

Before the design of the lightning protection system, a risk assessment must be performed by the protection engineer to determine the lightning protection class of the project. For this purpose, there are various standards in the world for risk assessment and air-termination system (ATS) design, one of the most comprehensive is IEC 62305 [24].

For risk assessment, several standards have been published in some countries. The NFPA risk assessment standard [25] has been developed in the United States. Also, France [26] and Spain [27] standards were developed, but these are not comprehensive. Some Australian standards such as AS1768 and AS5033 have also raised the risk assessment [28]. Ref. [29] investigates the LPS of PV power plants, but it does not address the main prerequisite of these calculations, i.e., risk assessment. In [30], a specific study of risk assessment in PV power plants is presented. The IEC 60364 standard [31] deals with the separate risk assessment of the surge protective device (SPD) and a computer program is also developed for active lightning protection [32]. In [33], a computer software has been developed, known as PVLPS, for risk assessment calculations specific to PV power plants based on the IEC 62305 standard, which is used in this paper.

This paper aims to present the comprehensive design principles of the LPS of PV power plants in 7 steps by using the results of a 40 MW project implemented in the center of Iran. First, the risk assessment of PV power plants for the project as one of the most complicated stages of this design is done by the PVLPS software. Then, based on the risk assessment result and the selected protection class, the number of ATSs is determined. In the next step, the earthing systems for lightning protection and the substation are designed using the ETAP software. Finally, passive and active LPSs are compared in the case of shading to adopt the most proper LPS for the project. To the best of our knowledge, considering all three items of risk assessment, LPS design, and earthing system design for a utility-scale PV power plant is less addressed. The results of this study will help protection engineers to improve the performance of the protection system of PV power plants, increasing the development of these systems.

2. Step 1: Risk assessment of PV power plant based on IEC62305-2 standard

Fig. 1 presents the risk assessment procedure based on IEC 62305-2 standard [24]. When conducting a risk assessment for PV systems, certain risks may not need to be taken into account. Given the non-flammable structure of PV systems, the risk of fire is generally negligible. Additionally, the likelihood of a direct lightning strike is low, as rooftop PV systems are typically installed on small buildings. Furthermore, in large-scale PV power plants, human presence is often limited, and therefore, the risk of human life loss (R_1) is typically not considered. Additionally, due to the relatively small capacity of PV systems, their failure does not usually impact public services, and as such, risk R_2 of public service loss can be neglected. Lastly, as PV systems are rarely installed in historical locations, the risk of cultural heritage loss (R_3) can also be disregarded. For off-grid solar systems, the risk of damage to heritage buildings R_3 is unlikely to be a concern. For grid-connected PV systems, in addition to R_3, the public services risk R_2 can be neglected. Consequently, the following parameters are calculated in the risk assessment procedure of PV systems:

- Solar farm: R_4
- Off-grid PV system: $R_1 + R_2 + R_4$
- On-grid rooftop PV system: $R_1 + R_4$

The risk assessment of large-scale PV systems requires careful consideration of various factors, while economic value loss is the most significant factor. Among the various risk components of R_4, R_A and R_U pertain to the possibility of animal loss, but these risks are often disregarded since PV systems are typically installed on rooftops or enclosed power plants. As a result, only R_B, R_C, R_M, R_V, R_W, and R_Z are taken into account. To mitigate the overall risk associated with a PV system and bring it to an acceptable level, the following measures can be taken:

- Installation of a coordinated SPD system in the low voltage (LV) line that enters the building can effectively decrease R_W and R_Z and
- Installation of a coordinated SPD system in the DC line of the PV system can reduce the R_M.

To further decrease the overall risk (R) of a PV power plant, it is advisable to consider installing an external lightning protection system in addition to the previously mentioned measures.

2.1. Risk assessment using PVLPS software

To perform the risk assessment, several parameters should be calculated and the IEC-62305 standard includes numerous tables to aid in the calculation of R_xs. To assess the risk of the 40 MW study project, PVPLS software [33] is used, which is developed by the authors of this paper specially for risk assessment of PV power systems based on Section 2. The length, width, and height of the project power plant are 1420, 500, and 3 m, respectively. The placement of PV panels is shown in Fig. 2.

Fig. 3 shows the first tab of the PVPLS, where the project parameters such as the number of stormy days per year, cable length, the way of structure installation and its surrounding environment, the installation method, and the installation environment such as whether it is inside the city or outside the city are entered to determine the number of dangerous events.

In the second tab of the PVPLS, the calculations of the probability of damage are performed, as shown in Fig. 4. In this tab, specifications such as the structure environment and type of LPS are entered and the probability of damage is calculated.

In the third tab, calculations of losses are performed. Information such as whether there is a possibility of ignition, explosion, or other accidents in the case of lightning and the type of fire extinguishing system are entered and the losses are calculated, as shown in Fig. 5. Finally, in the fourth tab, risk assessment calculations are done. As shown in Fig. 6, if the LPS class 4 is used, the PV power plant of the project is protected. Therefore, according to the risk assessment, the 40 MW study project requires the LPS class 4. However, a more conservative approach would involve selecting class 3, as it offers a higher level of lightning protection.

3. Step 2: Investigation of passive LPS

As the oldest and most extensive LPS, passive LPS is a lightning arrester which is invented by Benjamin Franklin in 1752 and is still used today. Simple Franklin rod, Jupiter lightning rod, and aerial wire terminal are classified as passive LPS. An LPS consists of the air-termination system, down conductor, and earthing system. The difference between active and passive protection systems is in the air-termination system. In the 40 MW study project, the height of the panels is 3 m, the height of the base of the structure to the ground is 2.5 m, and the protection class is 4. Fig. 7 shows a view of the panel and its structure.

As discussed earlier, incorporating an external LPS may be necessary to decrease the overall risk of a PV power plant. The ATS is a crucial component of an external LPS and typically comprises various components, including rods, spanned wires and cables, and meshed conductors [34]. The primary purpose of an ATS is to shield the PV structure from direct lightning strikes. A well-designed ATS significantly reduces the risk of damage to the protected area. According to [35], three techniques can be used to develop an effective ATS:

- Rolling sphere technique: This technique is universal and can be applied to complicated applications;
- Protective angle technique: It is proper for buildings with simple shapes, but has limitations on the height of the ATS; and
- Mesh technique: This technique is effective in protecting plane surfaces.

Fig. 1. Risk assessment based on IEC62305-2 standard.

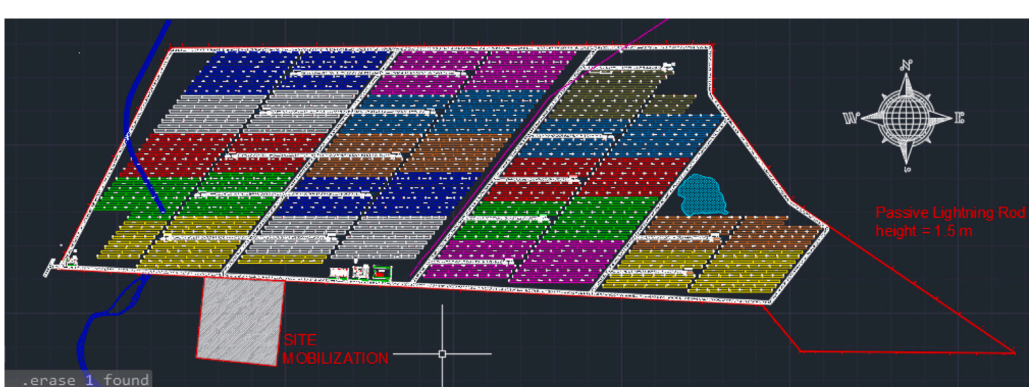

Fig. 2. Placement of PV panels in the 40 MW Study Power Plant.

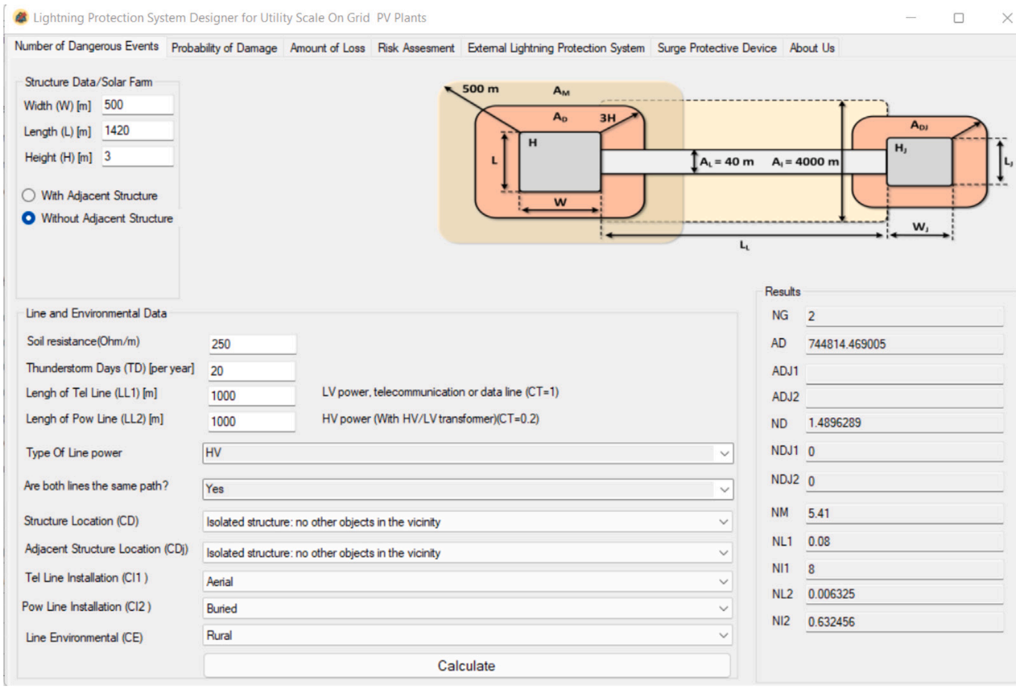

Fig. 3. Calculation of the number of dangerous events in the PVPLS software.

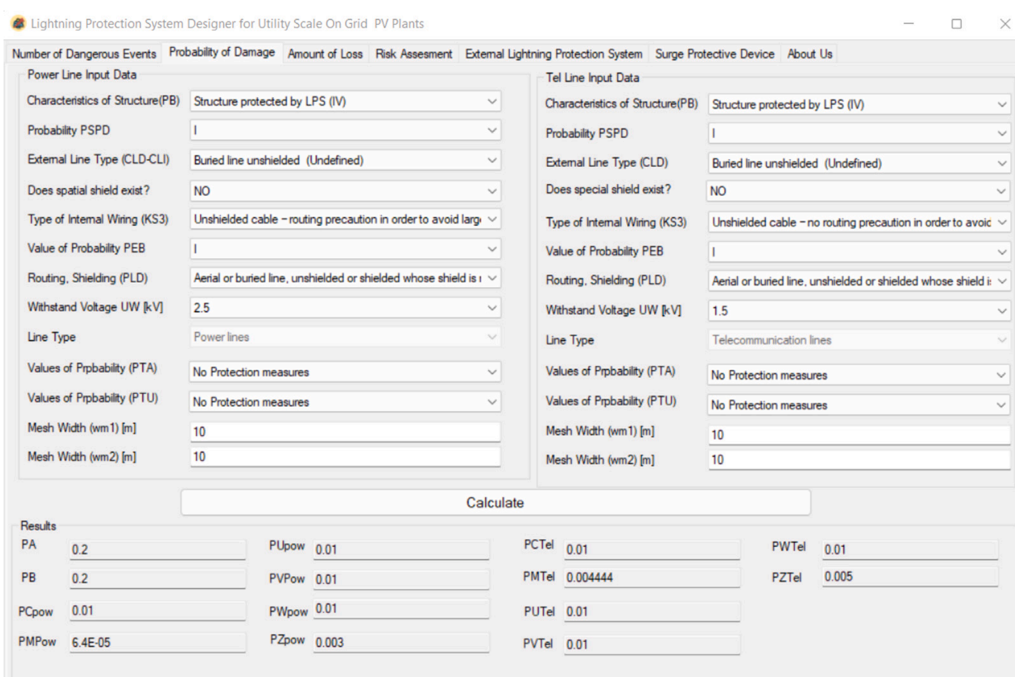

Fig. 4. Calculation of probability of damage in the PVPLS software.

These techniques are used to determine the best location for installing the ATSs, and based on the results, the installation location of the down conductors and earthing equipment is determined.

The LPS of PV power plants can be implemented in two ways: isolated and non-isolated. Isolated LPS uses protective measures, such as lightning conductors, to create a sufficient electrical and/or physical separation between the lightning current path and the protected structure. In contrast, conventional non-isolated LPS directly attach conductors to the structure or asset being protected, with little to no separation [36]. To accurately evaluate the performance of LPS, some factors such as the separation distance (SD) (as every metallic part within a distance smaller than the separation distance should be bonded to the down conductor), the depth of the rods, and the soil structure of the system should be investigated [22]. Therefore, an appropriate earthing system design is essential for an effective LPS.

3.1. Isolated LPS

In this method, the ATS is installed on a base with a distance greater than the SD from the panels. The cost of implementing the foundation

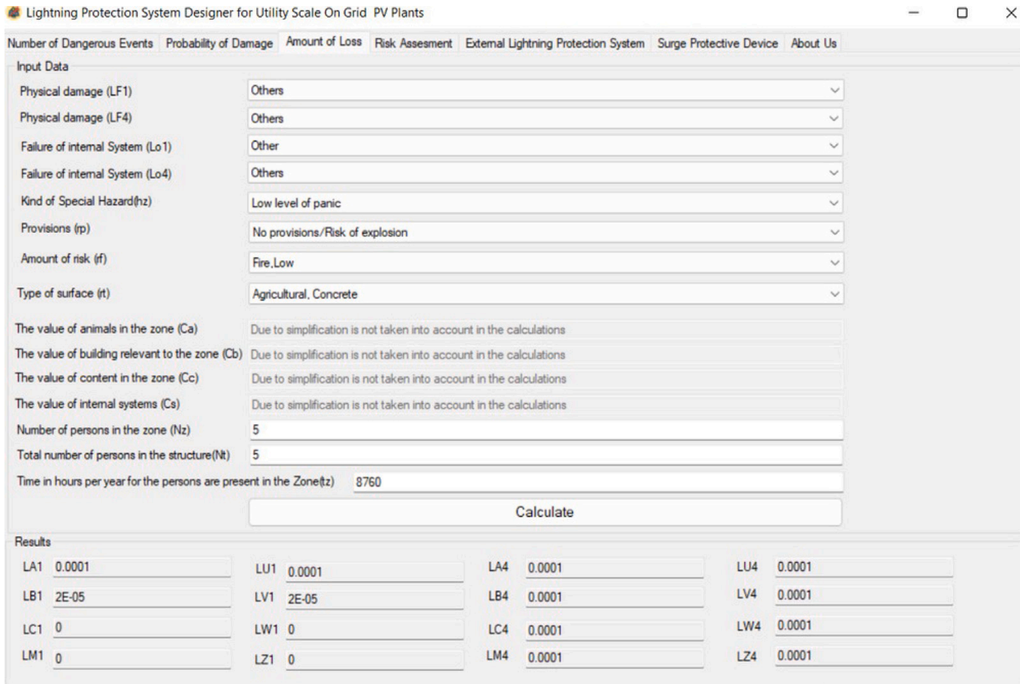

Fig. 5. Calculation of losses in the PVPLS software.

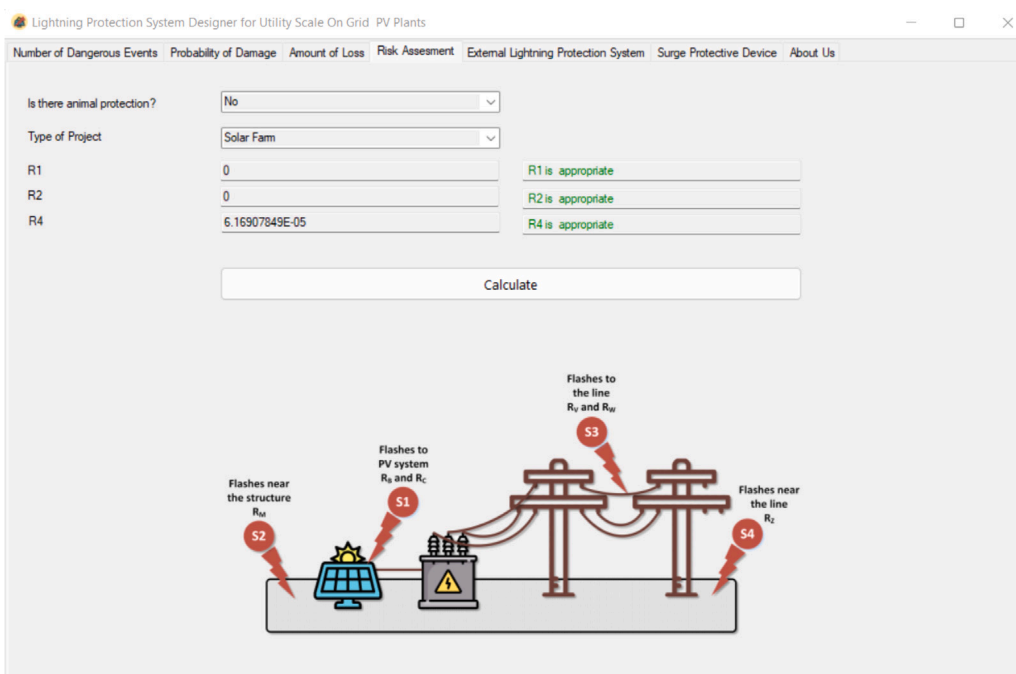

Fig. 6. Risk assessment results in the PVPLS software.

for the base, the base, and the 1.5 m lightning rod selected for this project should be considered; the cost of isolated LPS is higher than the non-isolated one. The specifications of isolated LPS of this project are as follows: the height of the base to the ground is 5 m, the protection class is 4, and the SD is 20 cm. Fig. 8 shows the implementation of isolated LPS. The isolated method can be implemented by making changes in the length of the base and lightning rod, as shown in Fig. 9; however, still, this method is not justified because of imposing additional costs of the base and foundation compared to the non-isolated method.

3.2. Non-isolated LPS

In this method, the lightning rod is installed on the structure at a distance greater than the SD from the panels. There is no need to implement the foundation for the base and the base, and the length of the lightning rod should be considered equal to 3.2 m with a height of 1.5 m over the panel. The cost of implementing this method is lower than the isolated one. In the non-isolated system, depending on where the lightning current hits, the direct strike can reach the ground

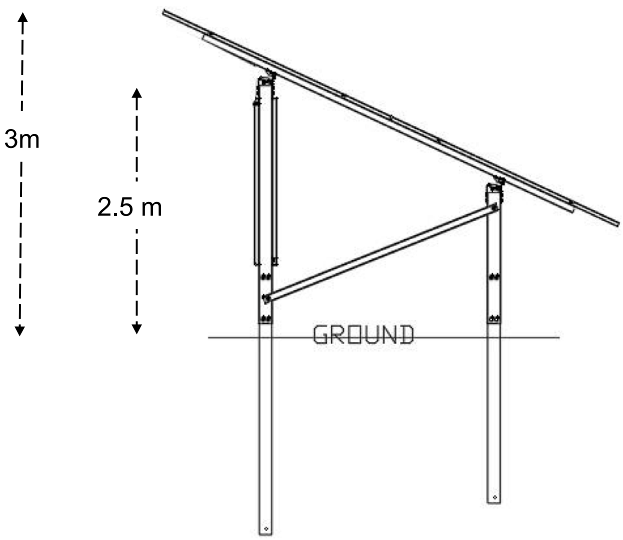

Fig. 7. Structure and PV panel side view.

through the metal structure of the PV system. Partial currents caused by lightning effects can also enter the DC system [37]. The specifications of the non-isolated LPS of the project are: the height of the panels is 3 m, the height of the base of the structure to the ground is 2.5 m, the length of the lightning rod is 2.3 m, the protection class is 4, and the SD is 15 cm. Fig. 10 shows the non-isolated LPS.

Regarding the wiring of the project, it should be noted that the magnetic field caused by the discharge of the lightning current at the strike location and around it and the down conductor causes an increase in overvoltage in the loop of the installed wires. This induction loop can include active or protective conductors. The longer the length of the loop, the larger the induced current. This current may enter the DC section and cause damage to the panels and inverter. Therefore, the protection design should be done in such a way that the length of the loop is as short as possible [38]. For this purpose, the length of the cables should be chosen as short as possible. The length of the DC side cable is considered for this purpose: the length of the positive and negative conductors should be at most 1 m and their distance from each other should be 10 cm [39].

The dimensions of the ATS must be checked in both methods. Also, it is necessary to consider the shading and partial shading conditions in both methods as follows.

3.3. ATS shading and partial shading effects on PV systems

Shading during some hours of the day or in the cold seasons of the year is a factor that reduces the power generation of PV panels. Therefore, it should be considered in the design. According to Appendix A of the IEC TR 63227 standard [32], based on the diameter of the ATS base, the minimum distance of the lightning rod base from the PV panel can be determined, where in this distance, the shadow is reduced significantly and can be neglected.

The (minimum) distance between the lightning rod/line and PV module a_f is calculated as

$$\frac{a_f}{d_f} = \frac{a_s + a_f}{d_s}, \tag{1}$$

where d_s is the sun diameter at the equator (1.39×10^9 m), d_f is the lightning rod/line diameter, and a_s is the distance between sun and earth (150×10^9 m). These parameters are shown in Fig. 11.

3.3.1. ATS shading effect on isolated LPS

According to the standard [40], the rod diameter and shading calculations are done. The minimum diameter of the air-termination system is 50 mm and the minimum distance between the lightning rod and the PV module rows is 5.4 m. In other words, if the distance of the next panel from the lightning rod is more than 5.4 m, the shading effect is insignificant. Since this distance in the project is 4.35 m (Fig. 12), the isolated method is not effective.

3.3.2. ATS shading effect on non-isolated LPS

According to the standard [40], in this case, the diameter of the rod should be 16 mm, and the minimum distance between the lightning rod and the PV panel is 1.7 m, which is acceptable. In other words, if the distance of the next panel from the lightning rod is more than 1.7 m, the shading effect is insignificant. Since this distance in the project is 4.45 m (Fig. 13), this method is effective.

3.4. Rolling sphere passive LPS

The rolling sphere technique is a widely accepted method for designing ATS. In this approach, the protective radius r_p of each lightning rod is determined based on the height of the rod and the highest point of the rooftop or power plant project as [41]

$$r_p = \begin{cases} r_s + \sqrt{2h_e r_s - h_e^2}, & h_r \geq r_s, \\ \sqrt{2r_s h_r - h_r^2} - \sqrt{2h_e r_s - h_e^2}, & h_r \leq r_s, \end{cases} \tag{2}$$

where r_s represents the rolling sphere radius, and h_e and h_r denote the maximum height of the equipment and the height of the rod, respectively.

In the 40 MW study power plant project, by applying a sphere with a 60 m radius in LPS class 4, ATSs should be installed in such a way that this sphere does not hit the panels, as shown in Fig. 14. In protection class 4, ATSs are placed at a distance of 20 m from each other, but this distance also depends on the height of the lightning rod. The use of 1.5 m ATSs can provide up to a 12.5 m protection radius.

Figs. 15–17 show the back and front views of design of passive LPS and design of passive LPS with protective radius, respectively.

3.5. Passive LPS cross-sectional area

In Table 6 Part 3 of the IEC 62305 standard, the minimum cross-sectional area (CSA) of the passive LPS for copper, aluminum, stainless steel, and hot-dip galvanized steel with a round section is 50 mm^2. However, for standing in lengths of 1.5 m or more, the minimum CSA of the passive LPS is selected to be 16 mm^2.

3.6. Down conductor

In the non-isolated method, according to Section 5.6.2 of the IEC 62305 standard, the minimum number of down conductors is two strings, i.e., two down conductor strings should be fixed to the structure at 0.5 m intervals and directed from both sides of the structure to the earthing system. In this standard, the minimum CSA of each down conductor for multi-stranded copper wire is determined to be 50 mm^2. In some circumstances, the metal skeleton of the structure as a natural conductor can be used as the down conductor or a part of it. In this case, the metal structure of the panels can be used as a part of the down conductor if the necessary conditions are met. In Table 6 of the mentioned standard, the CSA of these conductors for hot-dip galvanizing is determined to be 50 mm^2. In this case, the lightning rod is connected to the structure in the upper part, and in the lower part, the conductor of the earthing system is connected to the base of the structure. In fact, the structure between the arrester (air-terminal) and the earthing system plays the role of a down conductor. The CSA of 50 mm^2 can be provided with a belt with a thickness of 2 mm and

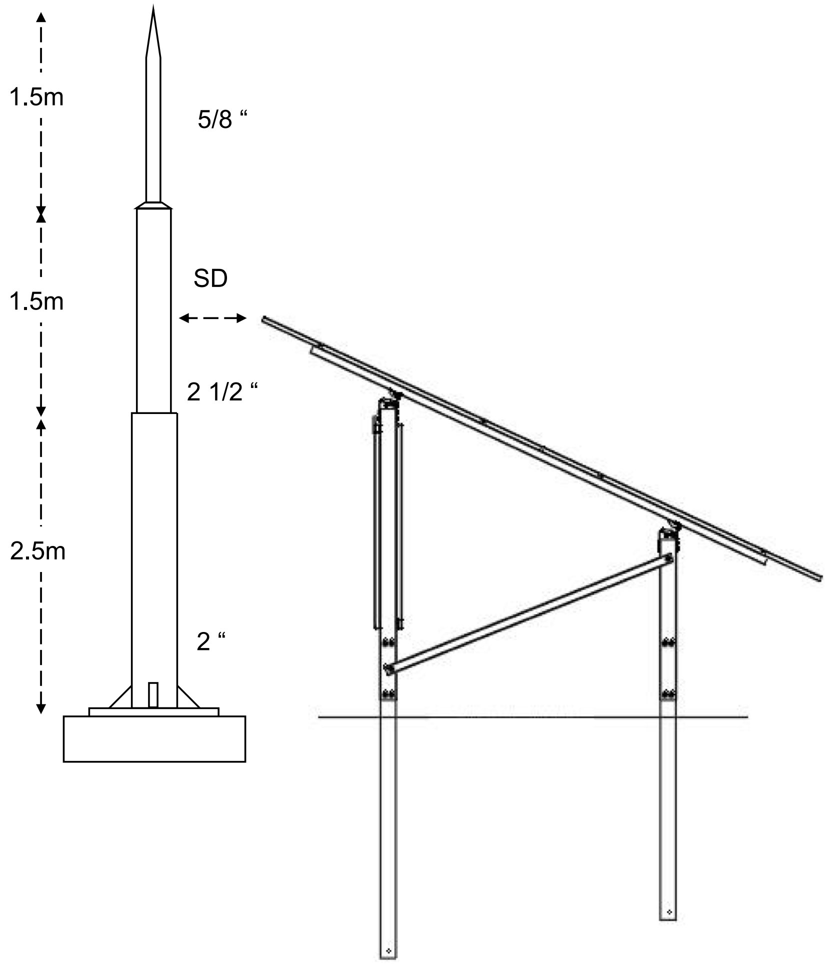

Fig. 8. Design of the isolated LPS in the PV power plant.

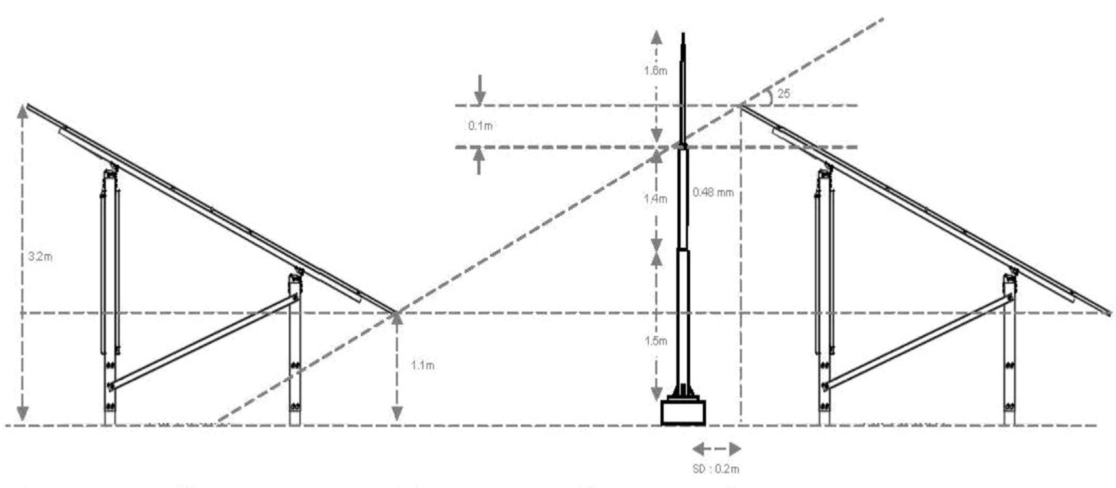

Fig. 9. Modified design of the isolated LPS in the PV power plant.

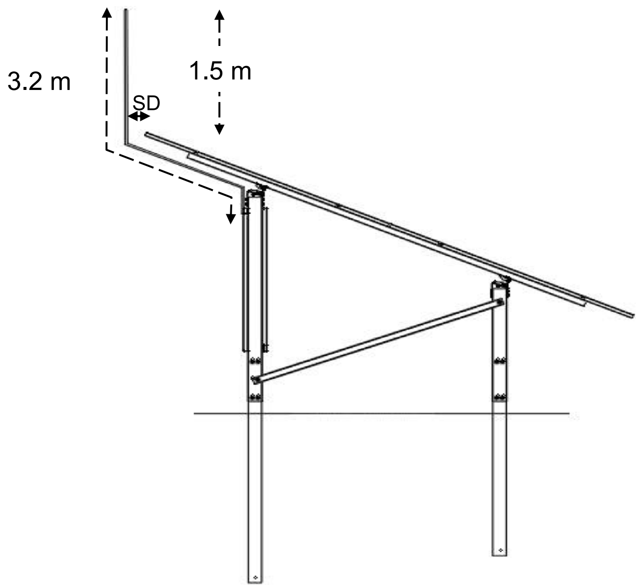

Fig. 10. Implementation details of the non-isolated LPS in the PV power plant.

a width of 25 mm. It should be noted that if the non-welded joints of the structure are not connected by jumpers, it is necessary to perform a continuity test to ensure the continuity of the entire structure for use as down conductors.

4. Step 3: Investigation of active LPS

Active LPS needs to be installed at a certain height for proper protective coverage. It means that in the protection radius of the active LPS, installation height, ionization radius (The radius of the ionizing sphere in active lightning rods, corresponding to the triggering time of the lightning rod, is 60 m for a 60 μs trigger time.), and protection class are important. Due to the limitation of the distance between the panels, the base and ATS shadings on the PV panel cannot be avoided. In addition to the mentioned cases, the diameter of the lightning rod is also a problem, and to prevent shading and partial shading, it is necessary to increase the distance between the panels again. Both factors of shading on the panel and increasing the distance between the panels reduce the efficiency of the PV power plant.

Fig. 18 shows the installation method of the isolated active LPS on a 7.5 m base. Conventional lightning rods are passive lightning rods, while capacitive or atmospheric lightning rods, which charge based on the electric field of the cloudy air, are considered active lightning rods. Active lightning rods must be installed on a base to ensure the required protection radius. The necessary height to achieve this protection radius should be considered, taking into account that the radius is based on the upper surface of the panels. Therefore, the height of the panels must be added to this value. For example, if the panel height is 3.5 m and the height of the section above the panels is 4 m, the total base height will be 7.5 m. Considering the length of the lightning rod, the height reaches 8 m. In other words, at the top of the panels with a height of 3 m, a protection radius of 79 m is provided (The protection radius of lightning rods with a Level 1 protective coverage and a triggering characteristic of 60, when installed on a 6 m base, will provide a protection radius of 79 m [26].). The minimum diameter of the ATS is 48 mm. According to the diameter of the pipe section used as a lightning rod base, the minimum distance between the lightning rod and the PV module to reach the minimum amount of shadow is 5.2 m, which is more than the available distance, i.e. 4 m.

Fig. 19 shows the design of active LPS in the 40 MW study project.

Table 1
Values of k_i according to IEC 62305-3 standard [42].

Protection Class of LPS	k_i
I	0.08
II	0.06
III and IV	0.04

Table 2
Values of k_m according to IEC 62305-3 standard [42].

Material	k_m
Air	1
Concrete and Tiles	0.5

Table 3
Values of k_c calculated by using the simple method [42].

Number of Down Conductors	k_c
1	1
2	0.66
3 and more	0.44

Table 4
Results of passive LPS design for the study PV power plant.

Rod height	Rod length	k_i	k_m	k_c	SD
1.5 m	3.2 m	0.04	1	1	12.4 cm

Structure height	k_i	k_m	k_c	SD
2.5 m	0.04	1	0.44	44 cm

5. Step 4: Calculation of minimum separation distance

Reliable electrical isolation of ATS, down conductors, and metal parts of the structure from internal systems is guaranteed if the safety distance s (refers to the minimum physical distance required to ensure sufficient safety from potential hazards, such as touch voltage) is maintained between these parts [34]. For this purpose, the separation distance (the minimum distance at which the possibility of a side flash is eliminated) should be considered larger than the safety distance:

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

where k_i is the protection level factor, k_m is the insulation coefficient of the material, k_c is the coefficient of the number of down conductors, and l (in meters) is the distance from the point where the separation distance is measured to the nearest bonding point for equipotentialization (the length of the down conductor from the desired point to the nearest bonding point). Tables 1 and 2 present the values of k_i and k_m according to the IEC 62305-3 standard [42].

To calculate k_c, there are two simple and detailed calculation methods [42]. Table 3 presents the values obtained from the first method.

Regarding the shape of the passive LPS installed on the structure of the panels, the actual value of the electrode is different from the value that is placed above the panel, and for calculation, the separation distance from the tip of the ATS to the connection point to the structure should be considered (Fig. 20). In this case, the use of a lightning rod with 3.2 m length and 1.5 m height over the PV panel is considered. Table 4 presents the study results.

6. Step 5: Earthing system of LPS

The IEC 62305 standard [43] states that the structure must be connected to the earthing system for the discharge of the leakage currents by this system and to prevent the unwanted disconnection of the circuit. For the proper functioning of the protection system, some factors such as the separation distance, the depth of the earthing rods, and the soil structure of the system must be investigated. In [22],

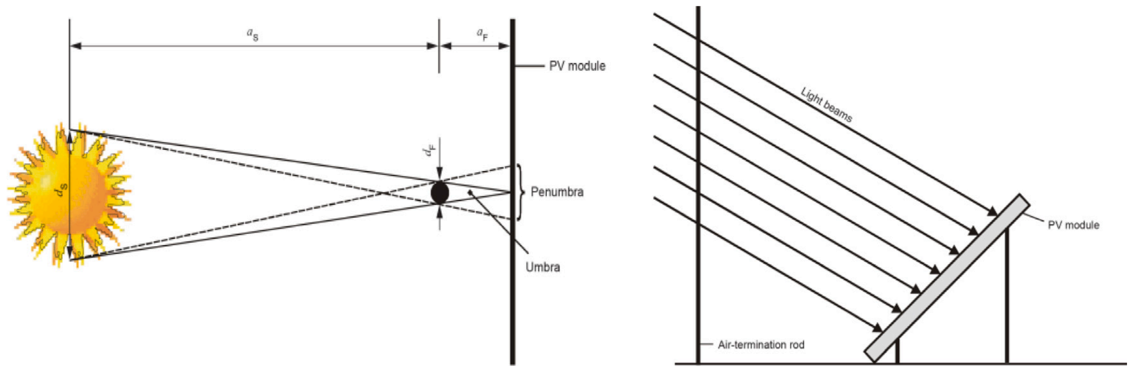

Fig. 11. Shading on a PV panel.

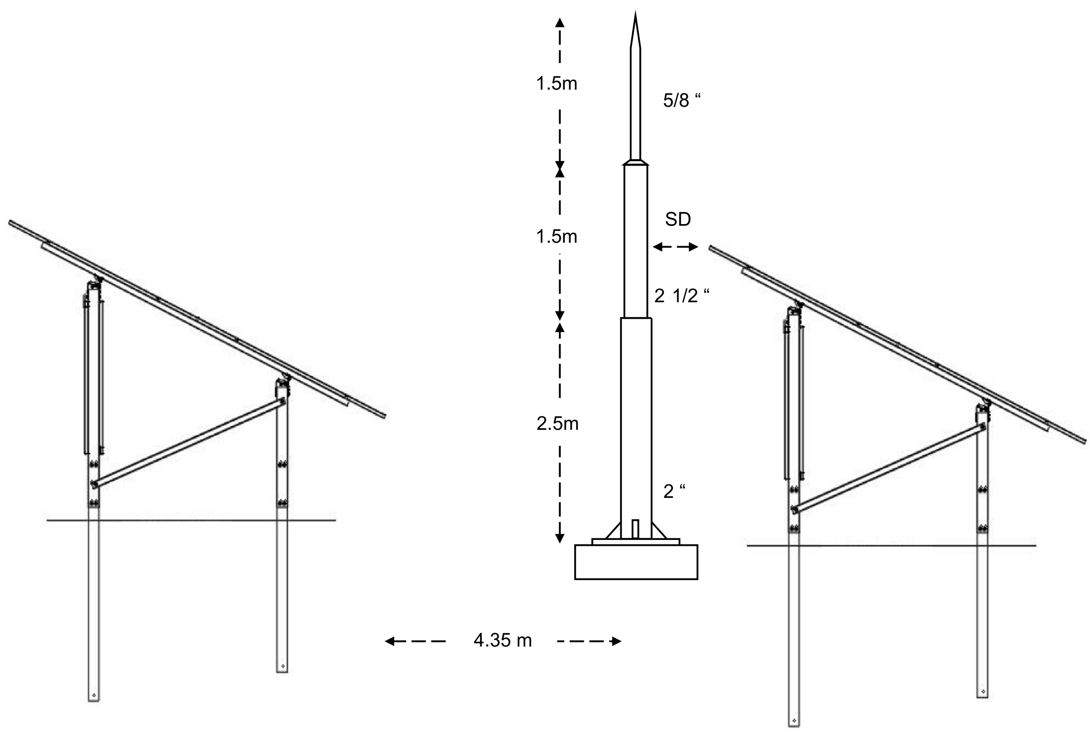

Fig. 12. Investigation of isolated LPS implementation in the PV power plant considering shading.

these factors have been considered and the following results have been obtained. Based on the measurement of the specific resistance of soil at 11 points and depths of 1 to 7 m, the average specific resistance of one meter of soil is about 900 Ωm (the average of the lowest layer, i.e., 7 m layer and 1 m layer of soil). Due to the wide area of the earthing system of the panels, the average of the total measurement points is considered. Additionally, by adopting the ring method, the minimum ring length is 31.4 m. To improve the condition of the earthing system, it is recommended to implement the ring at a depth of 1 m and to fill below the earthing conductor with a thickness of 10 cm with clay or bentonite:

- If a galvanized earthing electrode (round wire) is used, to control corrosion, the conductor should be surrounded by a 10 cm layer of high-quality concrete, preferably conductive concrete.
- In Table 5 of Chapter 3 of the IEC 62305 standard, the use of hot-dip galvanizing outdoors, concrete, and soils that do not contain high chloride is confirmed.

Fig. 21 shows the LPS earthing system. The simulation of one earthing system ring was done in ETAP and the results are shown in Fig. 22. The resistance of the earthing system is 0.215 Ω and the values of contact and step voltages are also acceptable (The standard does not specify much regarding the minimum length of the grounding system, except for the following section: Lightning current has a wide frequency spectrum, not necessarily with high frequencies. Therefore, the majority of the lightning current exists at lower frequencies.).

Fig. 23 shows the earthing system of the power plant with mesh configuration and the bonding of structures.

6.1. Earthing system of compact substations and transformers

Due to the large difference in the specific resistance in the area of the project site and regarding the arrangement type and depth of the earthing system implementation, it is necessary to collect the necessary information in the substation location and perform the calculations based on the report of investigating the specific resistance of the project site. Since the substations are located across the land and perpendicular to the measurement points of the soil studies, the closest measurement points to the substations are determined as E1 to E4.

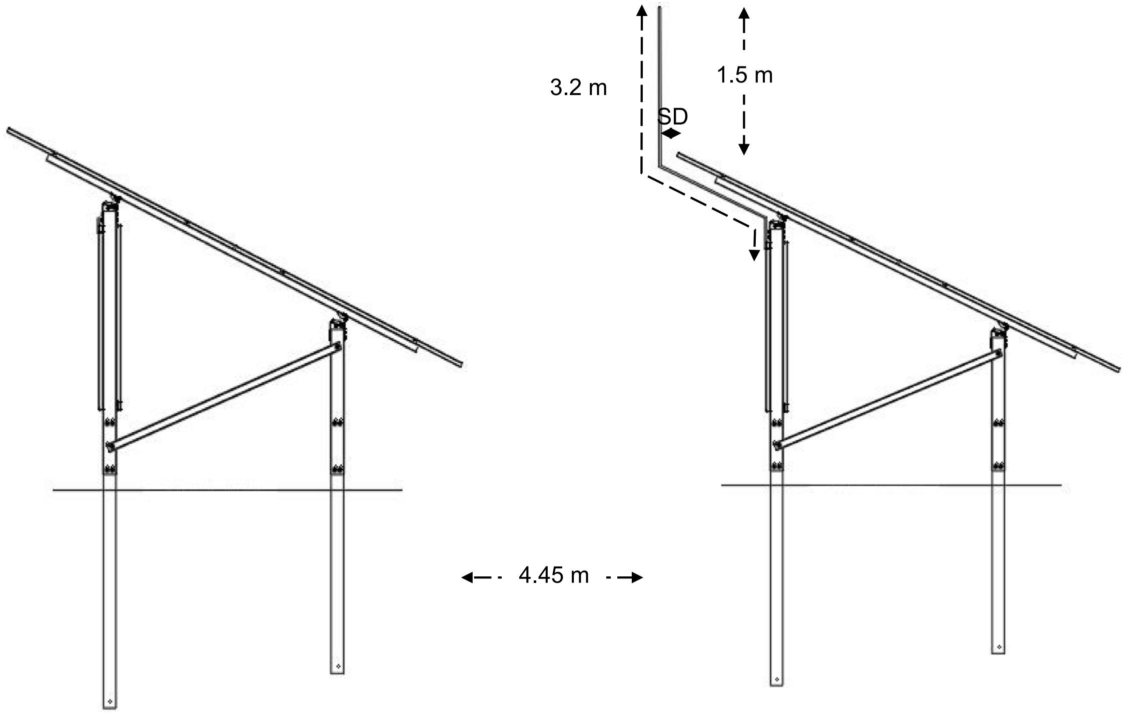

Fig. 13. Investigation of non-isolated LPS implementation in the PV power plant considering shading.

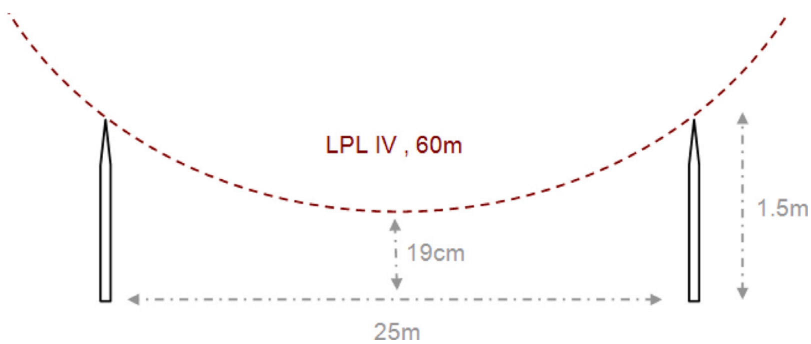

Fig. 14. Use of rolling sphere technique in the study PV power plant.

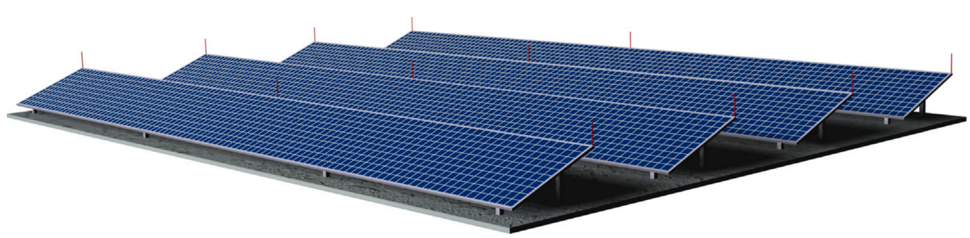

Fig. 15. Front view of design of the passive LPS in the study PV power plant.

Table 5
Investigation of various points of substation in the study PV power plant.

Points	E1	E2	E3	E4
Soil specific resistance at a depth of 2 m (Ωm)	933	290	257	92
Classification of substations based on the specific resistance of their local soil	Type 1	Type 2	Type 4	Type 3
Considered substations in four categories	Sub A1, Sub A2, Sub A3, Sub A4, Sub A5	Sub B6, Sub B7, Sub B5, Sub B4, Sub B3	Sub A6, Sub A7, Sub A8, Sub B2, Sub B1	Sub B8, Sub B9

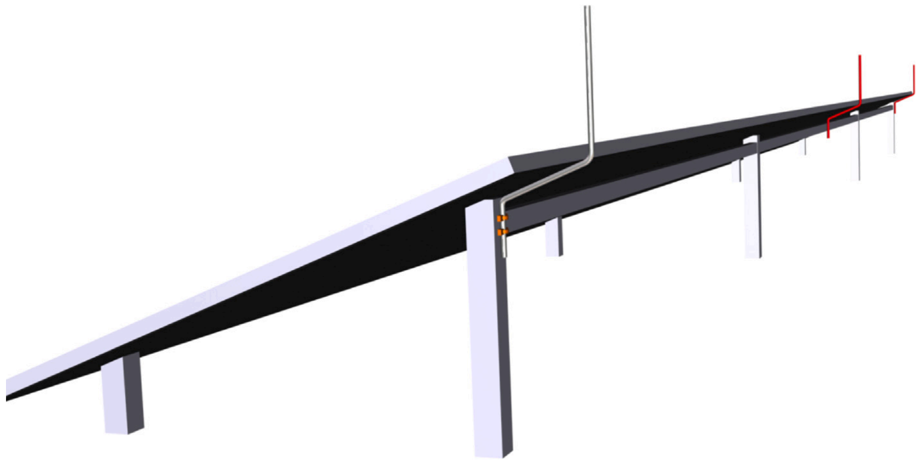

Fig. 16. Back view of the design of passive LPS with structure in the study PV power plant.

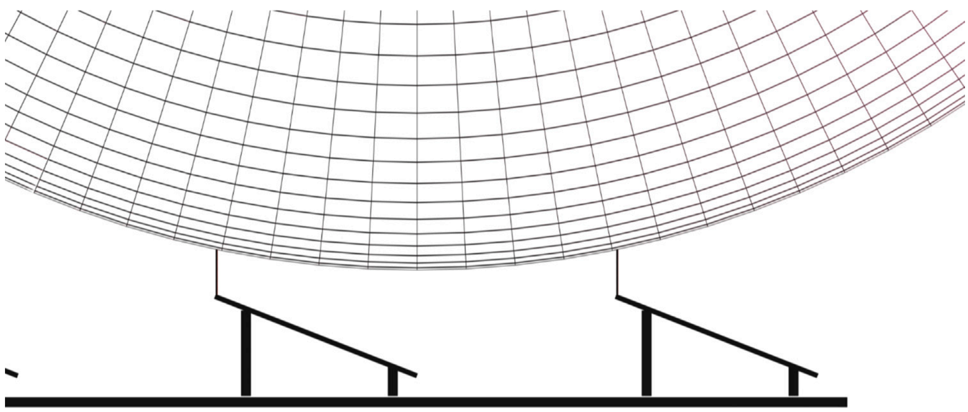

Fig. 17. Design of the passive ATS in the study PV power plant with protective radius (The area below the rolling sphere, which does not contact the equipment (but contacts the tips of the lightning rods), is considered the protection zone.).

The specific resistance values obtained in each soil type are used in the ETAP simulation and the proper design is prepared for the four existing soil types (Fig. 24).

The earthing system of the substations is implemented at a depth of 2 m so as not to hinder the implementation of the transformer foundation. In this study, six 3 m electrodes with a thickness of 16 mm are used for each substation, which can be replaced with the wire and plate. To reduce the step voltage effects, a 10 cm layer of materials with a specific resistance of 2500 Ωm is used. Providing a high-resistance surface layer helps reduce the effects of touch and step voltage within the system. Fig. 25 shows the substation, transformer, and LPS earthing system. Figs. 26–28 show the simulation results of the substation earthing system in ETAP.

6.2. Metal fence around the power plant

Power plant fences are generally connected either to their earthing system or to the existing earthing system. In general, the dedicated earthing system connected to the fence reduces the ground potential rise (GPR) and contact and step voltages. If it is possible to contact two hands (about two meters) between this fence and the equipment connected to the earthing system of the power plant, these two systems must be connected. In the case that the fence does not have a dedicated earthing system and is connected to the existing earthing system, contact and step voltages should be considered. For this purpose, the ring is implemented at a depth of 0.5 to 1 m in the perimeter of the fence of the power plant with a distance of 2 m from it and is connected to the fence at intervals of at least 50 m.

According to Section 6.6 of the EA TS 41-42 standard, fence bases that are installed up to one meter deep in the ground can be considered as the earthing system; however, it is necessary to provide electrical continuity between the parts of the fence. Also, the following points should be considered.

- In power plants located near the fence surrounding the electrical equipment, such as PV power plants, the fence must be connected to the earthing system separately.
- A ring is built around the fence with a distance of 1 m outside it and a depth of 0.5 m and is connected to it at intervals of 50 m along the length of the fence.
- The distance between the power plant and fence earthing systems should be at least 2 m.
- It is necessary to connect the corners and sides of the fence at a distance of 1 m where overhead power lines pass over it.
- The cables passing under the fence must pass through the metal pipe for at least 2 m and this metal body should be connected to the earthing system.
- The bonding cable between these two earthing systems must be visible.
- The hinged part of the fence doors should be bonded by flexible straps. The cross-section of the bonding cable should not be less than 16 mm^2.
- The ring is implemented in the area of the entrance and exit of the fence in such a way that it is implemented 1 m away from the doors when they are open.

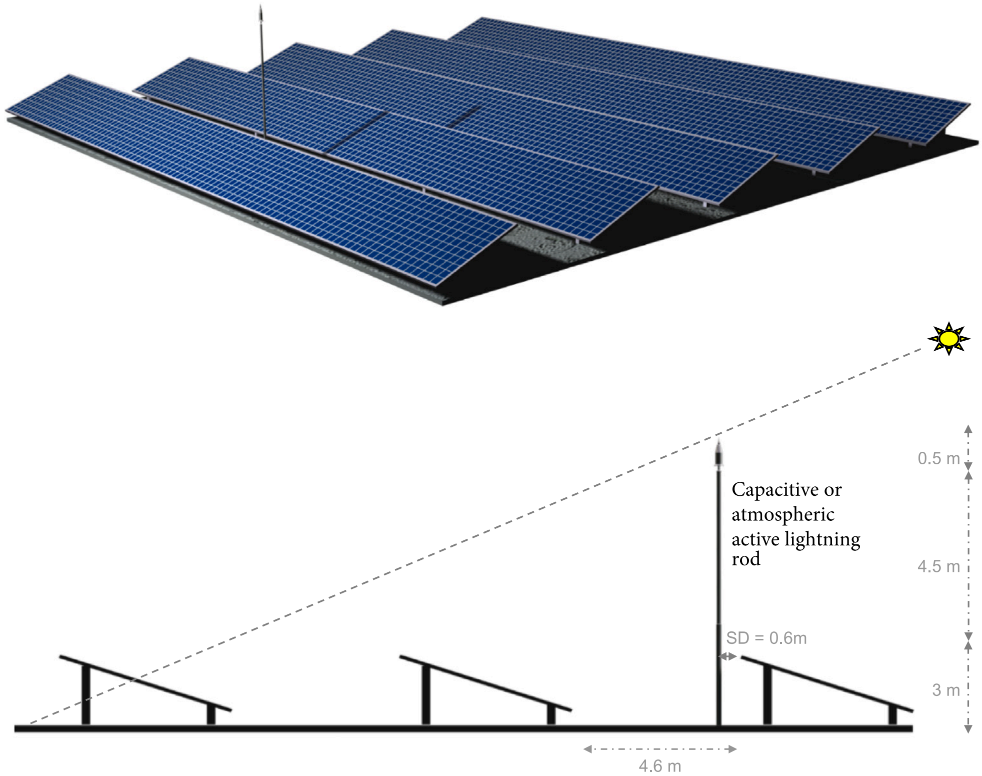

Fig. 18. Design of the active LPS in the study PV power plant.

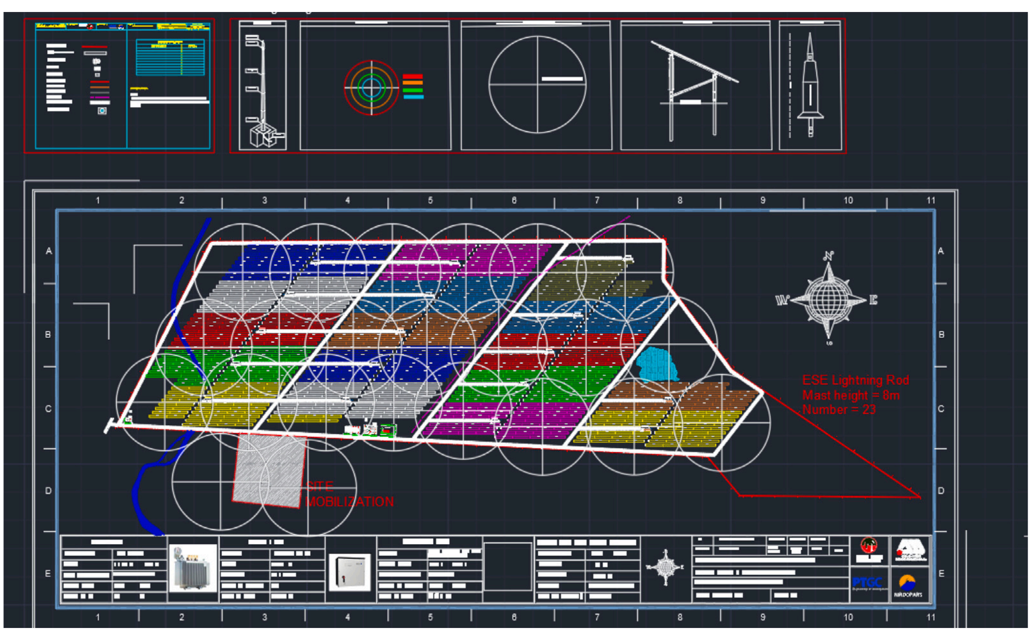

Fig. 19. Design of active LPS in the study PV power plant.

Fig. 29 shows the simulation of the metal fence of the power plant in the ETAP. The perimeter fence is considered as a single earthing system with a ring at a depth of 10 cm, and it was determined that in the case of a possible short-circuit, the maximum short circuit current is 40 kA (based on the information received from the employer), and in the case of a 0.5 s fault, the contact voltage, step voltage, and current density are higher than the acceptable values for a person with a weight of 50 kg. Therefore, the need for bonding the fence with the existing earthing system and implementing the surrounding ring according to the standard is evident.

6.3. Earthing connection of the metal shield of single-core cables

Usually, in medium voltage (MV) systems below 66 kV, the shield is connected to the earthing system on both sides of the cables. This bonding on both sides of the cables causes loop currents and creates noise in the system. To reduce this effect, there are several methods, one of the most well-known is to remove the earthing loop by bonding one side of the cables. The voltage difference between the cable shields and the earthing system should not exceed 65 V. According to the BS 7430 standard, for the metal shield of three-phase single-core cables,

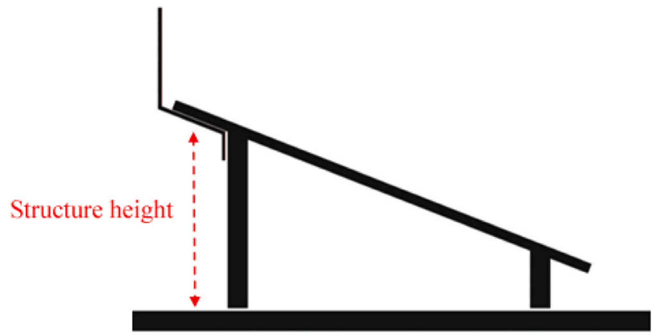

Fig. 20. Structure and installed passive LPS side view in the study PV power plant.

bonding is done on one side, and if the length of the cable is more than 500 m, bonding is done on both sides. Metal cable trays must be connected to the earthing system at intervals of 15 m. In addition, along the length of these trays, the bonding between the separate parts of the bonding tray is mandatory.

7. Step 6: Lightning protection of substations and transformer rooms

If the height of the substation building is less than 3.2 m, it is protected by ATSs installed on the panels, but since the height of the transformer building of this project is 4.2 m, it is necessary to implement an LPS for this building. To provide lightning protection for this building with protection class 4, two ATSs, one in the transformer building and the other at the end of the inverter canopy can be installed. The distance between these two lightning rods is 20 m. For each ATS, two down conductors (50 mm^2 twisted multi-stranded copper wire) are considered, which are connected to the structure by fasteners with 0.5 m intervals. Also, these down conductors are connected to the earthing system of the panels in the shortest path. Fig. 30 shows the lightning protection of the substation building.

Bonding the armatures inside the foundation should be also done to reduce the step voltage effect in the transformer room and inverters. The metal body of the inverters is connected to the earthing points connected to the bonding conductor inside the foundation at the closest point. Fig. 31 shows the earthing system of the substation building.

8. Step 7: Bonding of structure and panel

The following bonding points should be considered.

- Bonding between the nut-screw parts of the panel structure with 25 mm^2 coated wire;
- Bonding between the metal body of the panels and the structure with 16 mm^2 coated wire;
- Bonding between two structures with 25 mm^2 coated wire;
- The body of all DC boxes is connected to the structure ring from the closest point. In this way, during implementation, a conductor string connected to the earthing system by exothermic welding is pulled out of the ground at the base of these boxes and is connected to the body by a fastener.
- Bonding the separate parts of the inverter awning is done by jumpers with the 16 mm^2 cable.

8.1. Structure bonding

Since the distance between the tip of the ATS and its connection to the panel is 3 m, the separation distance is calculated, and since its value is less than the distance of 40 cm between two adjacent panels, there is no need for bonding from the separation distance point of view. However, to prevent metal–metal contact voltage (due to the distance of less than one meter, where it is possible to touch the two panels with two hands), two panels must be bonded as an extra bonding, as shown in Fig. 32.

Also, for all parts with non-welded connections in the structure and panel, the bonding should be done as shown in Fig. 33.

9. Summary of project protection design results

This section is dedicated to presenting a summary of protection design results for the 40 MW study power plant. The results of panel protection design against direct lightning strikes are presented in Table 6. According to the PVLPS software calculations, protection class 4 is selected. 1375 passive ATSs are required which are designed using the rolling sphere technique. It should also be noted that wiring management in the project can reduce many destructive factors during overvoltages and fault currents [44]. Tables 7 and 8 present the results of the LPS and substation earthing system designs, respectively. The number of substations is 17. The earthing system of the substations is provided at a depth of 2 m so that it does not obstruct the foundation of the transformer, etc. Six 3 m electrodes with a thickness of 16 mm have been used for each substation, which each one can be replaced by the wire and plate. To reduce the step voltage effects, a 20 cm layer of materials with a specific resistance of 2500 Ωm is used that can be gravel. According to the simulation results from the ETAP software, the size of the cables of the earthing system is checked, and to reduce the price, a suitable round wire is used instead of copper wire. The results show that the step and contact voltages and the overall resistance of the earthing system are in accordance with the standard and there is no contradiction in the provided outputs. The LPS mesh system for the panel set is 40 m width and the length of the panel set is implemented in the north–south direction. The transformer and substation earthing system set is connected to the panel mesh from four sides and completes the existing panel mesh. The material of the earthing system of the substations is copper with a size of 120 mm^2 (for a short-circuit current carrying capability of 40 kA), which is surrounded in a 10 cm layer with reducing materials with a specific resistance of 0.5 Ωm. Since the lower layers of the mesh affect the final resistance, it is better to place as much reducing material as possible under the ground conductor.

The results of this study can be listed as follows.

- In this design, since the earthing electrode is buried in the conductive concrete, in addition to dealing with the high specific resistance of the site soil and reducing the contact voltage, corrosion is greatly reduced.
- Due to the use of galvanized earthing electrode for the earthing system of ATSs, the cost is greatly reduced compared to the use of copper.
- Due to the increase in the height of the passive LPS from 1 to 1.5 m, the number of ATSs has decreased significantly, resulting in a reduction in the implementation and material costs.
- Due to the use of the non-isolated implementation method, the ATS base cost and the implementation of the foundation have been eliminated.
- The earthing system of the substations is placed within the extensive mesh of the LPS and completes the overall protection system. In this condition, two systems help each other in critical situations.
- Installing ATSs on the structure of the panels causes less current to pass through the metal body of the panel (compared to when the ATS is installed directly on the panel body).
- By using a metal structure with the necessary CSA as a down conductor (by bonding the parts of the structure with nuts and bolts), the cost of the down conductor (e.g., cost of 50 mm^2 copper wire) is eliminated.

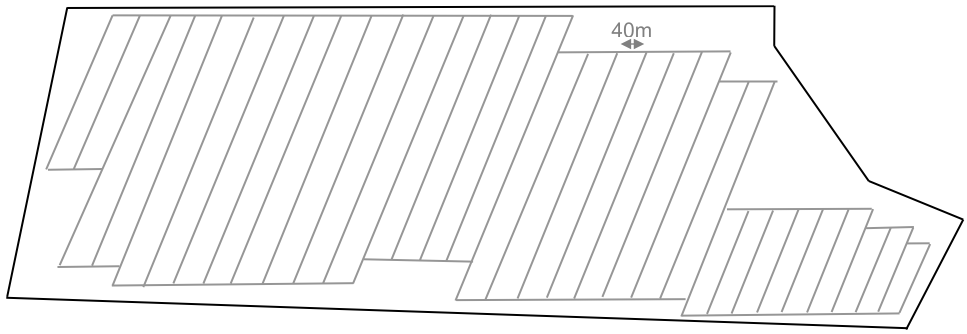

Fig. 21. LPS earthing system with mesh configuration for the study PV power plant.

Ground Grid Summary Report

Rg Ground Resistance ohm	GPR Ground Potential Rise Volts	Maximum Touch Potential					Maximum Step Potential				
		Tolerable	Calculated		Coordinates (m)		Tolerable	Calculated		Coordinates (m)	
		Volts	Volts	%	X	Y	Volts	Volts	%	X	Y
0.215	10787.9	666.3	199.4	29.9	149.0	361.1	2172.9	73.9	3.4	149.20	21.10

Total Fault Current	50.000 kA	Reflection Factor (K):	-1.000
Maximum Grid Current:	50.159 kA	Surface Layer Derating Factor (Cs):	0.816
		Decrement Factor (Df):	1.003

Fig. 22. Simulation results of one earthing system ring of the study PV power plant in ETAP. Simulation frequency is 50 Hz. Data are from distribution network company.

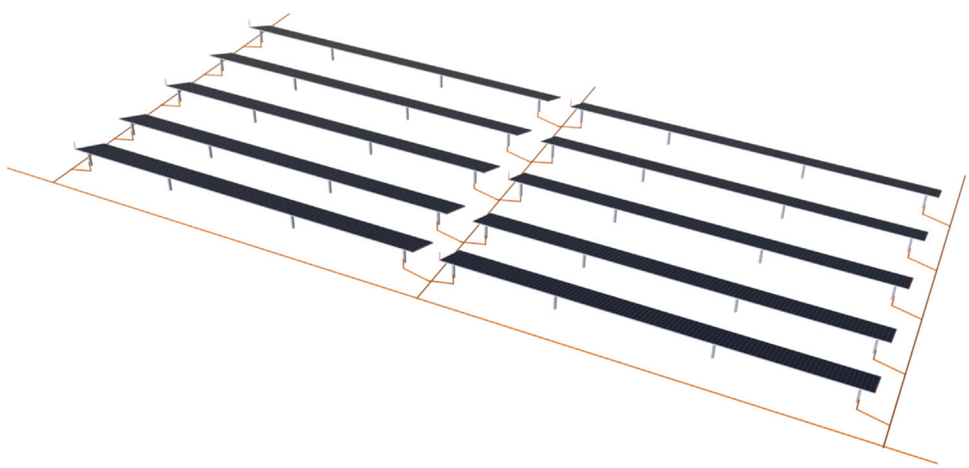

Fig. 23. Earthing system with mesh configuration and structure bonding in the study PV power plant.

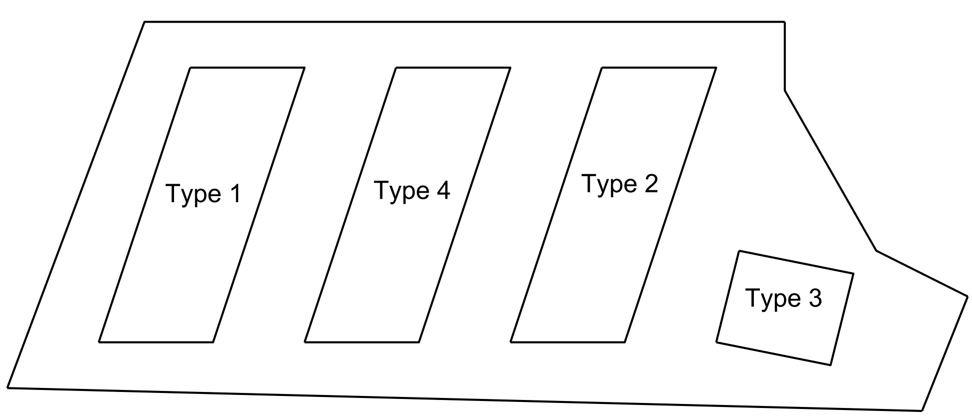

Fig. 24. Four existing soil types in the study PV power plant.

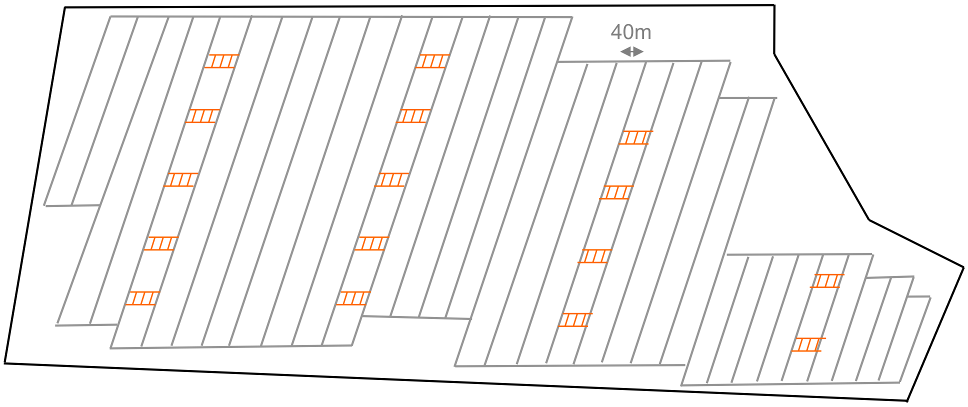

Fig. 25. Earthing system (red ladders) of the substation, transformer, and LPS in the study PV power plant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Ground Grid Summary Report

Rg Ground Resistance ohm	GPR Ground Potential Rise Volts	Maximum Touch Potential: Tolerable Volts	Maximum Touch Potential: Calculated Volts	Maximum Touch Potential: Calculated %	Maximum Touch Potential: Coordinates (m) X	Maximum Touch Potential: Coordinates (m) Y	Maximum Step Potential: Tolerable Volts	Maximum Step Potential: Calculated Volts	Maximum Step Potential: Calculated %	Maximum Step Potential: Coordinates (m) X	Maximum Step Potential: Coordinates (m) Y
0.176	7051.9	666.3	665.7	99.9	54.6	14.9	2172.9	98.1	4.5	54.90	15.00

Total Fault Current	40.000 kA	Reflection Factor (K):	-1.000
Maximum Grid Current:	40.127 kA	Surface Layer Derating Factor (Cs):	0.816
		Decrement Factor (Df):	1.003

Fig. 26. Detailed results of substation earthing system simulation for the study PV power plant. Simulation frequency is 50 Hz. Data are from distribution network company.

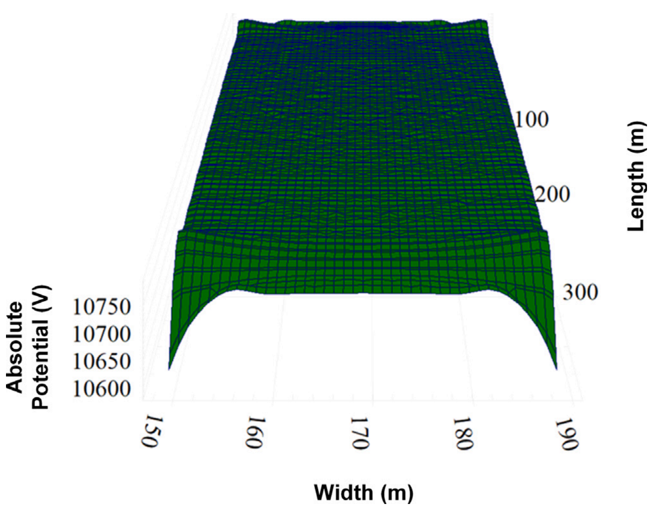

Fig. 27. Simulation results of absolute potential profile in the study PV power plant.

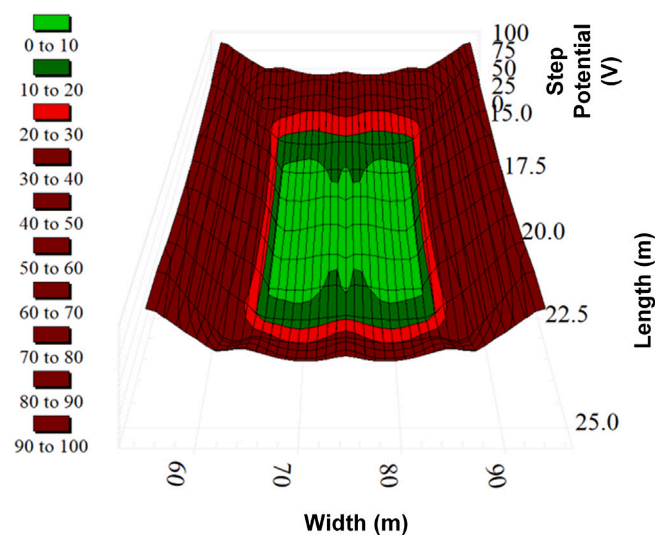

Fig. 28. Simulation results of step potential profile in the study PV power plant.

- Aluminum ATSs are chosen because they are light and cheaper than other metals.
- Due to low rainfall and dryness of the project site, galvanic corrosion caused by the connection of two dissimilar metals rarely happens (due to removing the electrolyte between them due to dryness).

Table 9 compares the conducted study with some previous works on the lightning protection of PV systems. This study includes risk assessment, investigation of both active and passive LPSs, and earthing system design for a utility-scale PV power plant.

10. Conclusion

This paper presents the design stages of the lightning protection and earthing system of a utility-scale 40 MW PV power plant in Iran. According to the installation distance of the panels, the calculations of

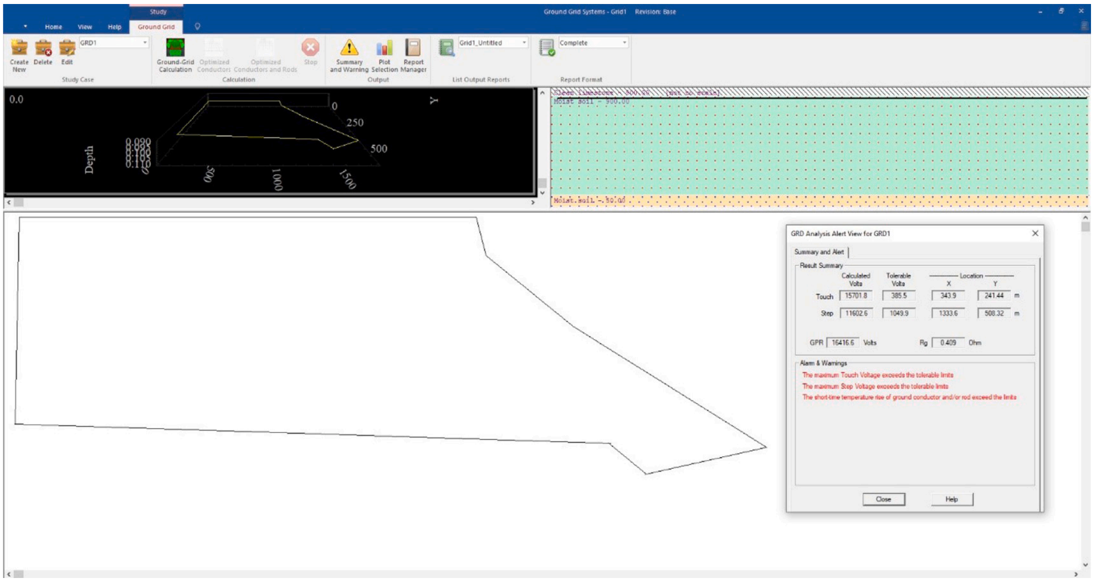

Fig. 29. Simulation of the metal fence of the study PV power plant as a ring.

Table 6
Results of panel protection design against direct lightning strikes for the study PV power plant.

Estimation of the probability of lightning striking the power plant	1 Strike per Year
Calculated protection level	Class IV
LPS method	Non-isolated passive LPS
Number of ATSs	1375 ATSs with 1.5 m height
ATS diameter	16 mm
Distance of ATSs	20 m and maximum 25 m
Soil specific resistance	The average is 890 Ωm at a depth of 1 m

Table 7
Results of LPS earthing system design for the study PV power plant.

Earthing System	Ring - Type B
Minimum Dimension of Calculated Ring	31.4 m
Dimension of Ring	Average dimension is 40 × 340 m - Perimeter is 720 m
Surface Layer	20 cm layer of material with a specific resistance greater than 2500 Ωm
Maximum Ground Fault Current	50 kA
Fault Time	0.01 s
Specific Resistance of Reducing Material	0.5 Ωm - Conductive concrete
Calculated Resistance	0.215 Ω - Simulated in ETAP
Permissible Contact Voltage for a Weight of 50 kg	666.3 V
Calculated Contact Voltage for a Weight of 50 kg	199.4 V
Permissible Step Voltage for a Weight of 50 kg	2172.9 V
Calculated Step Voltage for a Weight of 50 kg	73.9 V
Earthing Electrode	Hot galvanized, CSA 78.5 mm^2 (diameter 10 mm) - It is also possible to use uncoated copper wire of 50 mm^2
Reducing Material - Corrosion Reduction	Conductive concrete - Conductor buried in conductive concrete with a volume of 10 cm^3
Implementation Depth	1 m - The depth of frost is considered equal to 0.5 m

active and passive LPSs were done and it was determined that in the active method, shading is created on the panels, reducing the efficiency of the PV power plant. Therefore, the non-isolated passive method was used in this project. The simulation of the earthing system showed that if the galvanized earthing system is used instead of copper in the earthing mesh, the implementation costs are reduced. Risk assessment was done based on the IEC 62305-2 standard with PVLPS software, and the necessary simulations of the earthing system were done by ETAP software. From the economic point of view, by increasing the height of the passive ATSs, their number reduces, resulting in a reduction in the implementation and material costs. Also, the cost of the down conductor is eliminated by using a metal structure with the necessary CSA as a down conductor. The results of this protection design can be used as a useful basis for PV protection engineers. The optimal placement of ATSs, optimal selection of passive LPS method considering the economic aspect, and considering the effect of electromagnetic compatibility in the LPS and earthing system designs can be considered as future work. It is important to note that the presented work was

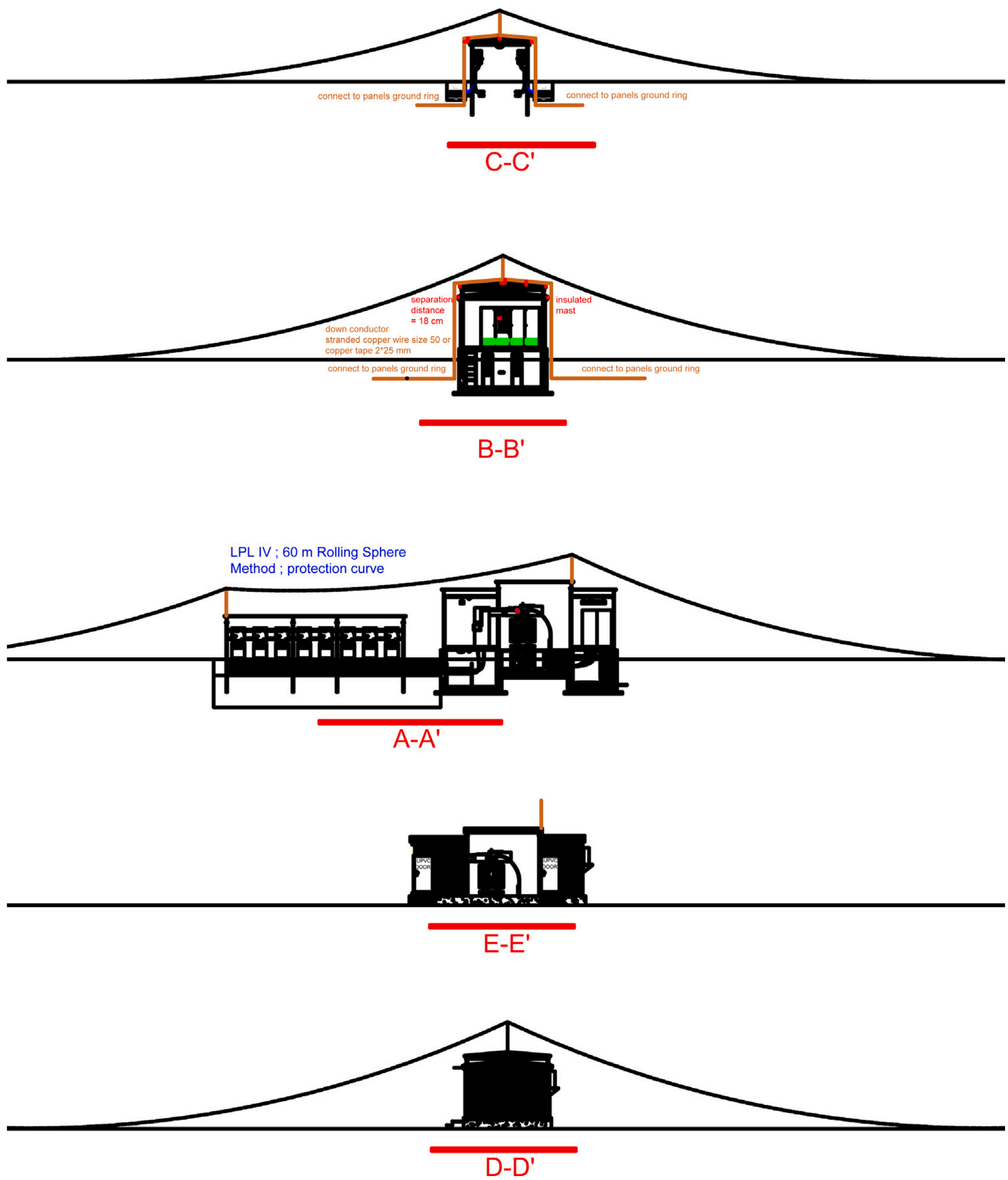

Fig. 30. Lightning protection of the substation building of the study PV power plant. Insulated mass is located at the center of the structure (on the roof), which is defined by applying a 60-meter rolling sphere corresponding to protection level 4. Since this sphere does not contact the structure, the structure is within the protection zone of this single electrode lightning rod.

based on IEC 62305 Edition 2, as this was the prevailing international standard at the time of the project execution. While IEC 62305 Edition 3 has since been introduced recently [45,46], the transition to this new standard is ongoing in many regions, and the principles and methodologies discussed in this paper remain highly relevant for practitioners working with Edition 2 during this transitional period. As future work, the methodologies and findings of this study could be re-evaluated and adapted based on the updated requirements and classifications of IEC 62305 Edition 3 to ensure compliance with the latest standards.

CRediT authorship contribution statement

Mohammad Parhamfar: Writing – original draft, Software, Investigation, Conceptualization. **Reza Naderi:** Visualization, Software, Investigation, Formal analysis. **Iman Sadeghkhani:** Writing – review & editing, Visualization, Software.

Declaration of competing interest

There is no conflict of interest for this article.

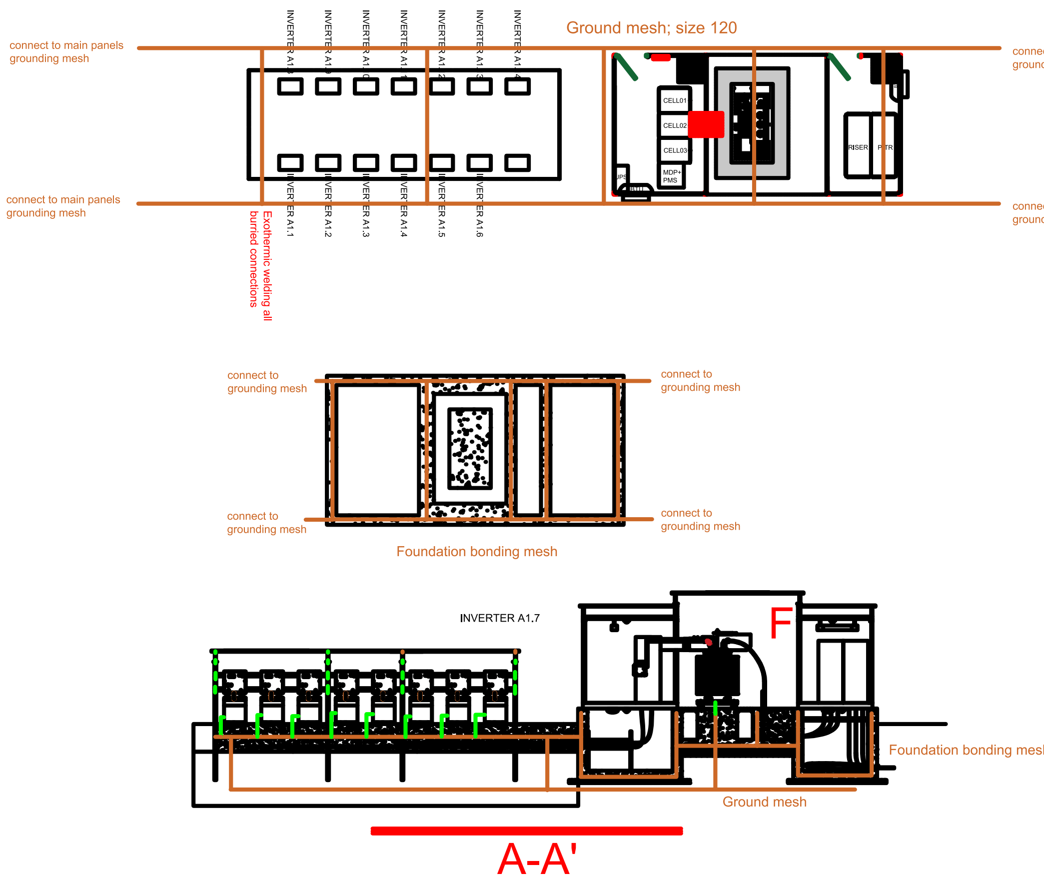

Fig. 31. Earthing system of the substation building of the study PV power plant.

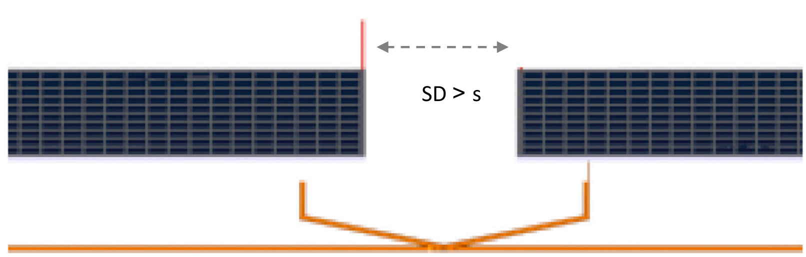

Fig. 32. Design of structure bonding in the study PV power plant. Since the separation distance is greater than the distance between two adjacent panels, there is no need to bond the two panels together.

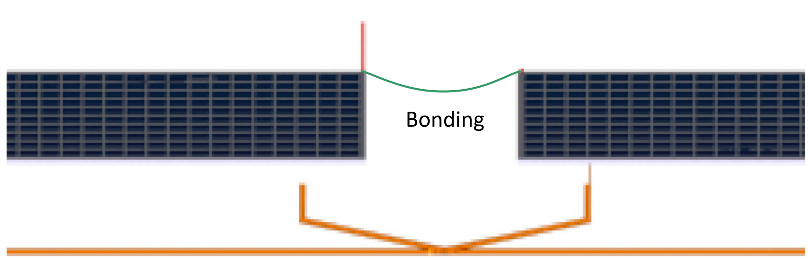

Fig. 33. Bonding for all parts of the study PV power plant with non-welded connection in the structure and panel.

Table 8
Results of substation earthing system design for the study PV power plant.

Soil specific resistance	Type 1: 933 Ωm - Type 2: 290 Ωm - Type 3: 92 Ωm - Type 4: 257 Ωm
Transformers and substations in each soil type	Type 1: Sub A1, Sub A2, Sub A3, Sub A4, Sub A5 - Type 2: Sub B3, Sub B4, Sub B5, Sub B6, Sub B7 - Type 3: Sub B8, Sub B9 - Type 4: Sub A6, Sub A7, Sub A8, Sub B1, Sub B2
Earthing system	Mesh and electrode (rods)
Dimension of ring	two 10 × 10 m loops
Surface layer	20 cm layer of material with a specific resistance of more than 2500 Ωm
Maximum ground fault current	40 kA
Fault time	1 s
Specific resistance of reducing material	0.5 Ωm - Conductive concrete
Calculated resistance	0.232 Ω - Simulated in ETAP in type 1
Permissible contact voltage for a weight of 50 kg	666.3 V
Calculated contact voltage for a weight of 50 kg	568.1 V
Permissible step voltage for a weight of 50 kg	2172.9 V
Calculated step voltage for a weight of 50 kg	140.4 V
Earthing electrode	Copper wire with a CSA of 120 mm^2 - six 3 m copper rod electrodes (copper coated steel) with a diameter of 16 mm
Reducing material - Corrosion reduction	Conductive concrete - Conductor buried in conductive concrete with a volume of 10 cm^3
Implementation depth	2 m - To pass through the foundation of the substations

Table 9
Comparison of the conducted PV lightning protection study with some previous works.

	[21]	[22]	[23]	[32]	Conducted study
Is risk assessment performed?	X	X	X	✓	✓
Are both active and passive LPSs investigated?	X	X	X	X	✓
Is earthing system design considered?	✓	✓	✓	X	✓
Is a utility-scale PV plant studied?	X	X	X	X	✓

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