A novel lightning mast layout to eliminate shading effect on PV panels

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ABSTRACT

Globally, solar energy technologies are increasingly being implemented. The appeal of photovoltaic (PV) systems lies in their ability to efficiently convert sunlight into electricity, making them popular among homeowners, manufacturers, and businesses. To maximize the output of a PV system, it is crucial to install the panels in a location with ample sunlight exposure and minimal shading. Typically, PV panels are mounted on rooftops to avoid shading which exposes the system to the risk of lightning strikes during storms. To mitigate this risk, engineers implement direct lightning protection measures. This paper focuses solely on direct lightning protection methods, discussing the importance of the earth grid and the factors influencing its effectiveness. Additionally, the paper introduces a new layout for lightning masts for PV systems with back-to-back east and west panel orientations where space constraints limit the separation of PV rows. This approach is considered novel as it cannot be found in any published peer-reviewed works. A detailed case study is also presented which supports the introduced equations when it comes to design and compliance to direct lightning strikes. Additionally, the implementation of equations 2 to 12 simplifies the work for designers to ensure lightning compliance using the rolling sphere method.

1. Introduction

In recent years, there has been a significant rise in the deployment of Photovoltaic (PV) systems in the market. This increase can be attributed to the concerted efforts of organizations like the United Nations, governments, and researchers to develop technologies that help combat the impact of greenhouse gases on the environment [1,2]. PV systems have the ability to convert sunlight into electrical energy [3,4]. To maximize the capture of solar energy, PV systems are typically installed in open areas to avoid shading and enhance efficiency [5]. However, due to the large area required to generate electrical energy for heavy loads, PV systems are more susceptible to lightning strikes, which can result in severe damage to the infrastructure [6,7]. To safeguard against lightning strikes, it is crucial to implement direct lightning protection measures, such as employing lightning masts, and adequate earth grid [8–10]. The effectiveness of the earth grid is heavily influenced by the soil resistivity of the installation area, which can vary with changes in temperature and humidity [11–14]. Therefore, it is essential to consider these factors when designing the lightning protection system (LPS) to ensure compliance, especially during stormy seasons. Without a robust earthing system, there is a high risk of lightning protection failure, leading to potential damage to the PV system. The current peer-reviewed published work focuses on various aspects of lightning protection for PV systems,

including performance on rooftop grid-connected systems, ground-located systems, impact on inverters, and hybrid PV systems [15–20].

The current research has a gap in addressing direct lightning protection for PV systems without any spacing between panels. Under this layout, the panels are installed facing east and west with back-to-back touching. While orienting panels east and west can enhance system output [21], it poses challenges in meeting lightning protection requirements, particularly in rooftop installations. This paper proposes a novel layout for direct lightning protection using the rolling sphere method, aiming to bridge this gap while ensuring unhindered sunlight to the panels. The proposed method introduces equations to support the innovative approach for horizontal lightning masts and addresses earth grid requirements under varying moisture conditions. The equations provided by the paper enable engineers to configure the panel setup for east and west orientations using just three sets of data while ensuring compliance with direct lightning strike protections. Furthermore, the paper delineates the overarching requirements of the Earth Terminal System (ETS) and elucidates the potential influence of environmental factors on soil resistivity, thereby affecting the resistance value of the ETS. A case study is also included to demonstrate practical application.

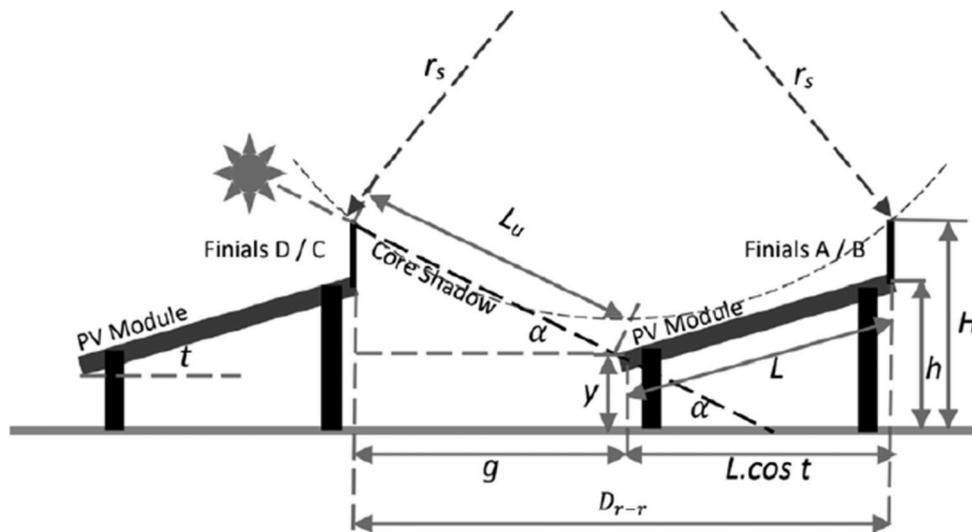*E-mail address:* mohamadnassereddine@uowdubai.ac.ae.

Fig. 1. Lightning side rod to avoid shading on panels [28].

2. Theoretical analysis

The primary goal of direct lightning protection is first to capture and then to provide a secure pathway for lightning energy, preventing damage to the PV system. Lightning energy has the potential to inflict severe damage on PV systems, as well as transfer to buildings, posing a threat to both structures and individuals. As per the IEEE standard [14], a lightning strike initiates by ionizing the air, leading to the formation of stepped leaders that act as conduits for charges from the cloud to the air. The return stroke, visible as a bright flash in the sky, then propagates upward [14]. The design for direct lightning strike protection comprises three key components as per [14].

1. Air Terminal System
2. Down-Conductor System
3. Earth Terminal System

This paper outlines the essential requirements for an air-termination system to minimize or eliminate shading on panels and the introduction requirements of an earth terminal system.
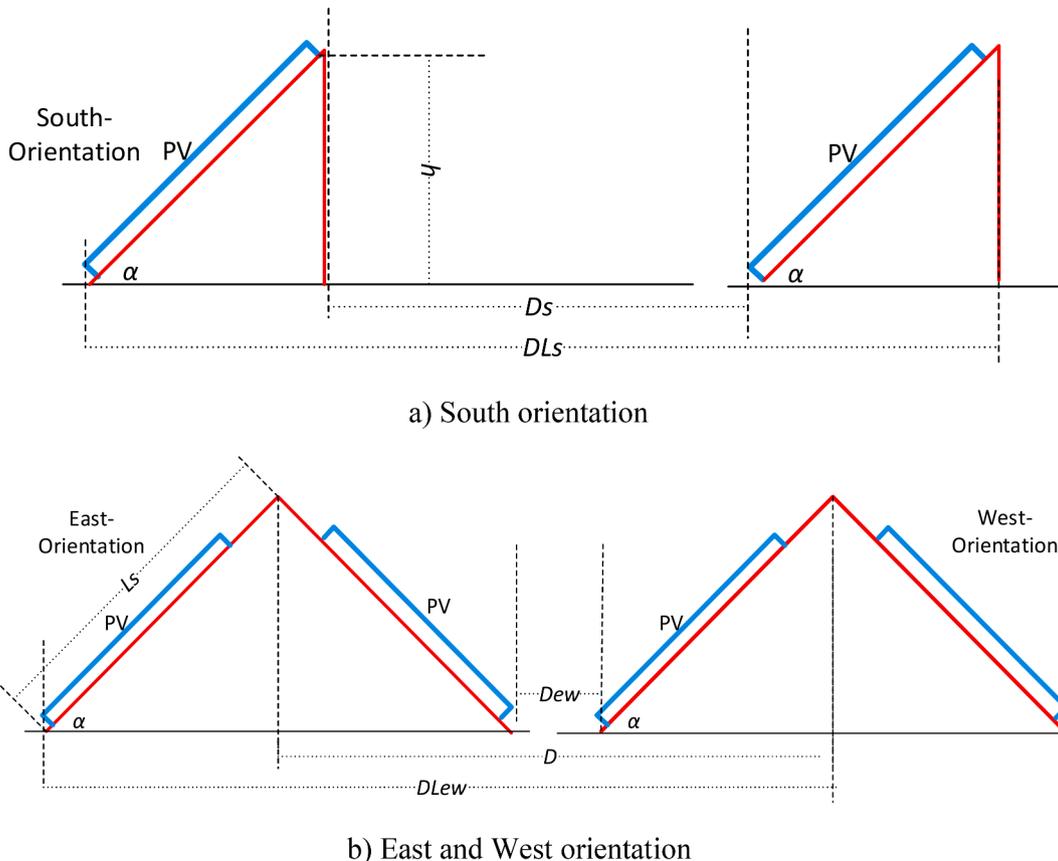

a) South orientation

b) East and West orientation

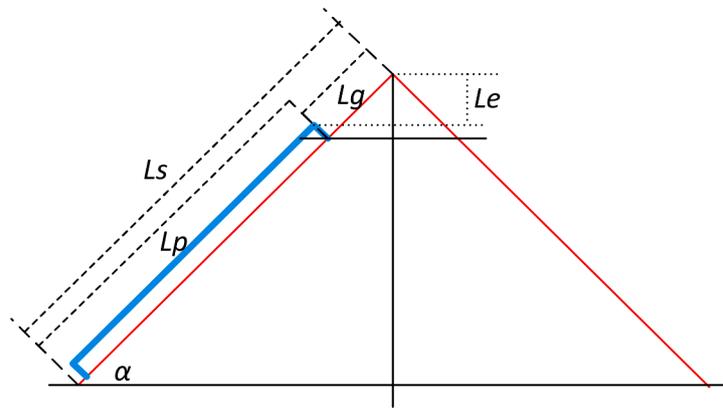**Fig. 2.** a) South orientation PV panels b) East and west back-to-back panel orientation.

Fig. 3. Location of the PV panel on the steel structure.

2.1. Air-terminal system

The destructive potential of lightning energy poses a threat to infrastructure. The extensive layout of PV systems in open areas increases their susceptibility to lightning strikes. One effective mitigation strategy is the installation of lightning masts [22]. These masts serve to intercept lightning strikes before they reach the PV panels directly. Current industry practice involves erecting tall masts, or lightning rods, that extend several meters above the panels to intercept the strikes [23–25]. This approach is deemed appropriate as long as the panels are adequately spaced to prevent shading. Fig. 1 illustrates this practice, showcasing the acceptable separation between panels and masts [26–28]. It is permissible to extend the masts as long as the required distance from the panels is maintained. It is important to highlight that the literature review exclusively references vertical masts or rods as a means of capturing lightning energy and guiding it safely to the ground [22–28]. It is worth noting that Fig. 1 is just to show the literature layout of the vertical mast or rods. The paper scope is not to assess any of its variables.

In a scenario where solar panels are installed back-to-back, with one side facing east and the other facing west, the traditional installation of lightning masts (as shown in Fig. 1) is not feasible without causing shading on the panels. This shading can lead to hot spots and decreased panel efficiency. Fig. 2a) illustrates PV panels with a south orientation while Fig. 2 b) illustrates the layout of panels in this east-west configuration. When the panel is configured as depicted in Fig. 2 b), a walkway is incorporated between the rows to facilitate cleaning and various types of inspections. The suggested walkway width typically ranges between 30 and 40 cm., This study presents a new method to protect against direct lightning strikes without causing shading during midday. The innovative approach involves installing horizontal lightning masts along the panel length instead of vertical ones. In this setup, the panel structure will be connected to the lightning system's ETS. It is worth noting that based on the current literature review, no cited work follows the paper approach when it comes to lightning design. Also, no cited work captures similar equations that support the novel lightning direct protection layout.

2.2. Proposed air terminal system layout

Placing the panels east and west is favorable under numerous working conditions especially if power is required morning and afternoon. Also, the east-west layout can generate more power especially when the available area is limited and in areas close to the equator [29]. Placing the panels facing east and west eliminates the required space between strings except for maintenance and cleaning purposes. The distance for the maintenance under this paper is presented by D_{ew} within Figure 2. The separation between the panel strings is defined by Ds and it

should meet Eq. (1). h is defined by Eq. (2). These equations were derived by analyzing Figure 2.

$$Ds \geq 2h \tag{1}$$

$$h = L_P Sin(\alpha) \tag{2}$$

where

α is the tilt angle of the panel
Ds is the separation
Eq. (3) determines DL_S while Eq. (4) determines DL_{ew}:

$$DL_S = D_S + 2L_P cos(\alpha) \tag{3}$$

$$DL_{ew} = D_{ew} + 3L_S cos(\alpha) \tag{4}$$

where

L_P is the panel length.
L_S is the length of the steel for east and west orientation as shown in Figure 2

The presented theoretical works allow the reader to compare the string separation requirements by using DL_S and DL_{ew}. The inclusion of these equations adds significant value to the theoretical assessments in the paper. They enable assessment for both south orientation as well as east and west orientations, enhancing the comprehensiveness of the research. It is worth noting that the existing literature review equations cannot be used for east and west panel orientations as illustrated in Figure 2-a.

The work under this paper goes into more detail to determine the required separation from the top of the structure to the panels. The introduced equations help with the explanation of the required setup to meet the proposed lightning mast layout. Analyzing the setup in Fig. 3 allows for the generation of Eq. (5).

$$L_g = \frac{P_{wth}Cos(\alpha) + L_e}{sin(\alpha)} \tag{5}$$

where

P_{wth} is the thickness of the panel
The value of L_e will be set by the designer. Under this paper, the L_e value is two times the width of the panel P_{wth}. Therefore, under this paper, Eq. (5) is rewritten as Eq. (6).

$$L_g = \frac{P_{wth}(Cos(\alpha) + 2)}{sin(\alpha)} \tag{6}$$

The length L_S is found using equation 7

$$L_S = L_P + L_g \tag{7}$$

Including Eqs. (6) and 7 is crucial for designers to successfully complete the steel design while meeting lightning protection standards
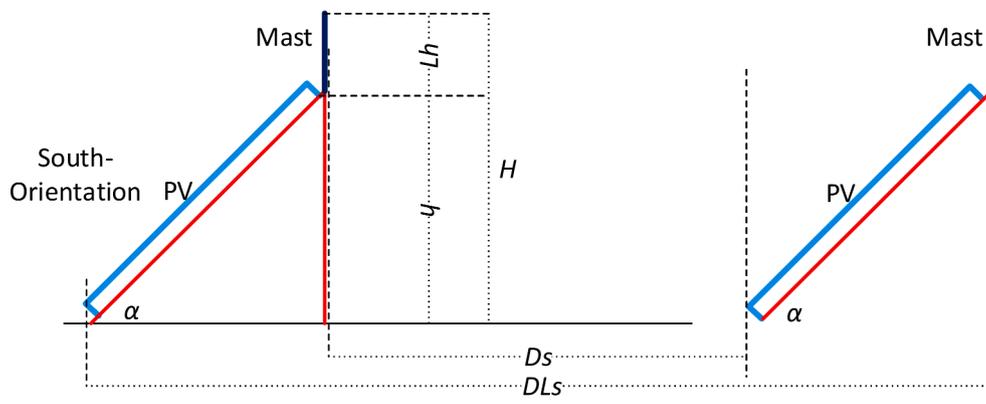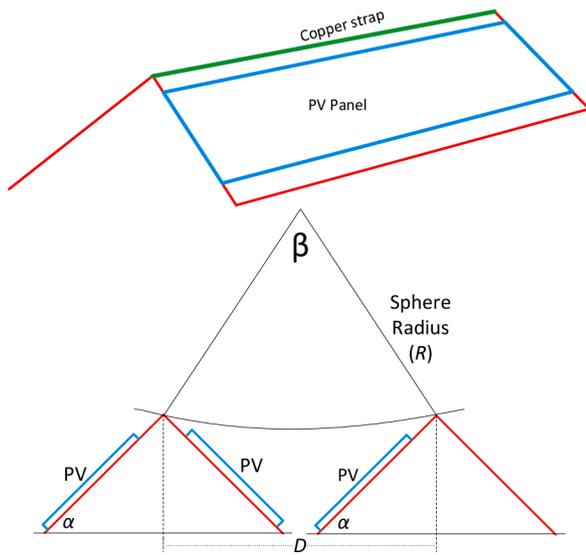
Fig. 4. Lighting mast on top of the panels.

Fig. 5. Proposed horizontal lightning strap.

Table 1
Lightning strike radius as per Australian standard [30].

Lightning protection level (LPL)	Sphere radius (m) R	Interception current (kA)
I	20	2.9
II	30	5.4
III	45	10.1
IV	60	15.7

The lighting mast layout proposed in this paper will not affect the DL_{ew} length. Fig. 5 displays the suggested arrangement of the horizontal lightning mast. The copper strap positioned on top of the panels intercepts lightning strikes. Drop conductors will be installed to meet IEC and IEEE standards, ensuring a safe path for the lightning energy to reach the ground.

In Figure 5, the copper strap intercepts the direct lightning strike and safely discharges it to the ground. It is worth noting that the PV panels always be installed within the steel frame of the designed steel structure. This reduces/eliminates the risk of lightning strikes reaching the panels from the sides. Eqs. (10) and 11 are derived in the paper from Figure 5 to calculate the angle β as a function of the separation between the center of the panel strings D. The angle β allows the reader to understand the angle that will be established for different lightning protection levels (LPL) under different panel sizing and layout.

$$D = D_{ew} + 2 \times L_S Cos(\alpha) \qquad (10)$$

$$\beta = 2Arcsin\left(\frac{D}{2R}\right) \qquad (11)$$

where:

R is the rolling sphere radius as per Table 1 [26]
Eq. (12) is generated by combining Eqs. (10) and 11:

$$\beta = 2Arcsin\left(\frac{D_{ew}}{2R} + \frac{L_S}{R} + \frac{Cos(\alpha)}{2R}\right) \qquad (12)$$

Fig. 6 illustrates the variation of β under different circumstances. The data indicates that β remains small in value across various panel lengths. It is crucial to note that the chosen panel length conforms to the current industry norms for PV installations. With the slight angle observed, it is logical to infer that the lightning sphere will not interact with the PV panels, particularly within the parameters established by this paper for L_e. With these all considered variations, the rolling sphere never touches/reaches the panels under the paper-proposed air terminal system (ATS).

2.3. Earth terminal system (ETS)

Since early 1900, the earth has formed an indispensable part of the

and avoiding shading on the panels. The work under this paper adheres to the IEEE-998 rolling sphere methodology. Eqs. (6) and 7 are formulated to support Eqs. (8)–12 to guarantee that the panels are located within the protection area of the rolling sphere method. Eqs. (11) and 12 include the radius of the rolling sphere to effectively links these equations to the rolling sphere method. Without these equations, the necessary guidance for structuring the steel design layout in compliance with direct lightning protection would be lacking. The theoretical insights presented in this context significantly enhance the existing literature by filling this specific gap and providing valuable contributions.

Fig. 3 facilitates the analysis of panels oriented towards the east and west. In order to enable a comparison between the analysis of panels facing south and those facing east-west, Fig. 4 illustrates the layout of lightning rods for the south-facing orientation. As illustrated in figure 4, h will be replaced by capital H. and H is defined by Eq. (8).

$$H = h + Lh \qquad (8)$$

Under this condition, Eq. (1) will be rewritten as Eq. (9). Under this condition, the separation between the panel strings will be increased as Ds is increased which impacts on Eq. (3). It is important to highlight that vertical lightning masts or rods do not necessitate spacing from the panel [22–28]. Consequently, the inclusion of L_g is unnecessary in this scenario.

$$Ds \geq 2H \qquad (9)$$
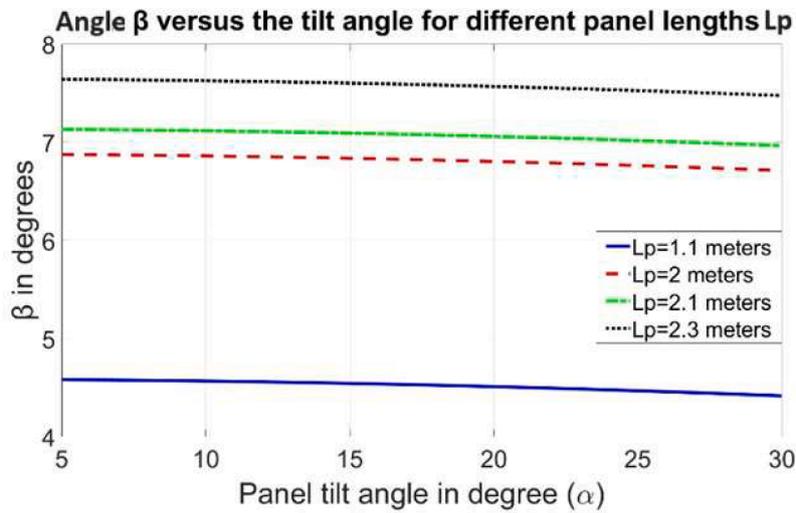
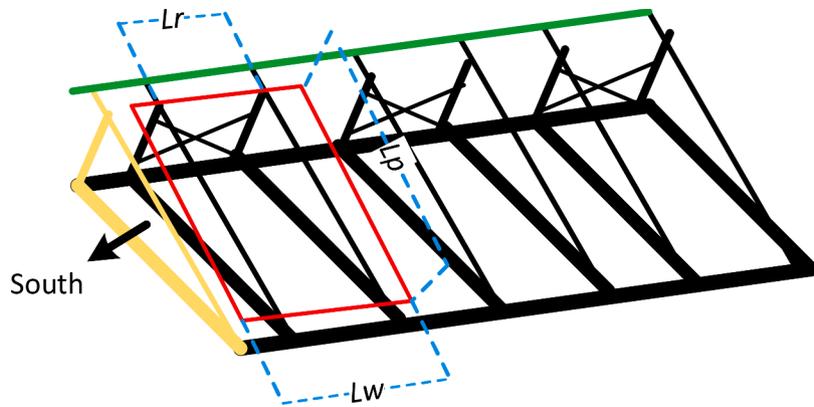**Fig. 6.** β for different tilt angle α.

Fig. 7. Panel installation layout showing the horizontal copper rod.

electrical system. The earth is relied on for numerous activities which include in general ground systems. The primary function of the earth grid system is to safely absorb lightning energy without causing damage to the properties. This system is established by placing electrodes and mesh conductors in the ground. The configuration and intricacy of the earth grid system are influenced by the soil resistivity, which depends on the location and can vary due to factors such as temperature and humidity For adequate earth grid layouts, the reader can refer to published works [14,31–33].

3. Discussions

The paper focuses on direct lightning protection using horizontal rods made of copper straps. These rods are physically connected to the steel support structure of the panels. Typically, panels have two steel supports on which they are fixed to prevent movement during windy seasons. This setup ensures that the length of the horizontal copper rod is kept short and varies depending on the length of the panel (*Lw*). Fig. 7 illustrates the layout of the proposed horizontal copper rod for panels,
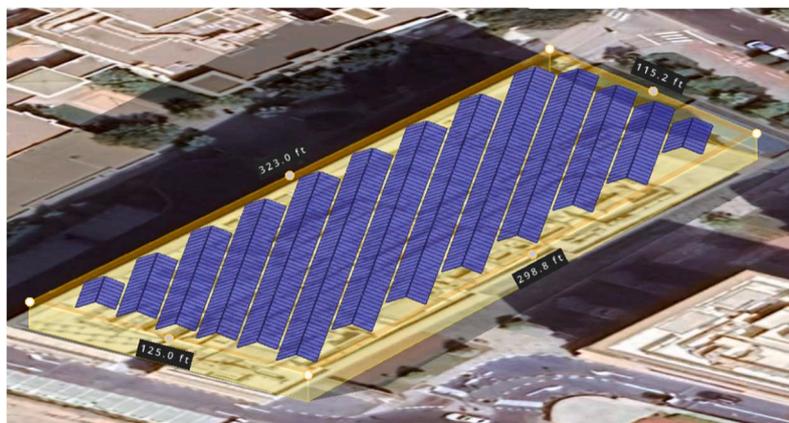

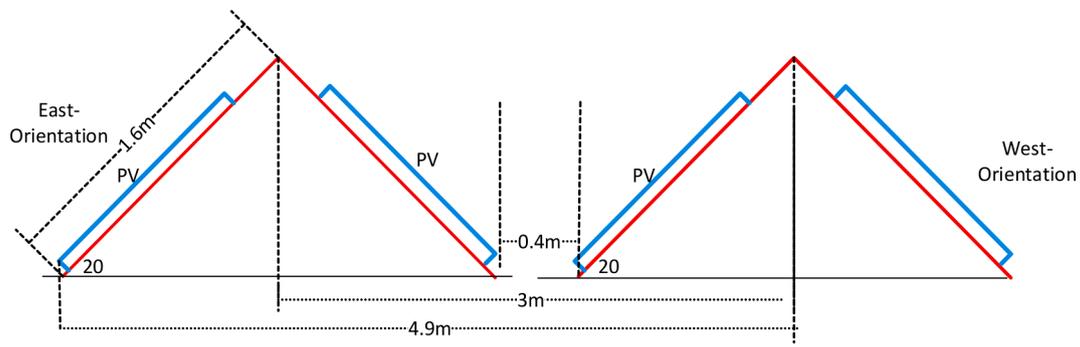**Fig. 8.** Panel installation facing East and West orientation.

Fig. 9. Case study layout dimensions of panel string.

which can be installed in either portrait or landscape orientation, resulting in *Lw* varying between 1.3 m and 2.17 m. These lengths are based on panels up to 600 W in the current market. In the design, the steel supporting the panels will have smaller dimensions than *Lw*. The design can ensure that the distance between the copper rod support structure, denoted by *Lr*, falls between 0.9 m and 1.3 m.

In order to provide comprehensive protection for the panels, the steel structure is extended towards the south, as depicted in Fig. 7, and similarly towards the north orientation. This extension ensures that the panels are shielded from all sides, enhancing their overall protection.

The following considerations are crucial to address during the design stage, although they fall outside the scope of this paper:

- Ensuring that the selected copper strap, rod, or shield wire does not sag under its own weight or heavy wind conditions. Based on the layout proposed in Figure 7, designers may consider using copper-clad steel rods as long as they meet the necessary current-carrying capacity and are resistant to damage from lightning strike energy. These types of rods or straps offer strong tensile strength.
- The distance between the drop conductors must adhere to relevant standards and policies as outlined in the reference [34].

4. Case study

The case study focuses on a photovoltaic (PV) system installed on the roof of a warehouse. The PV panels will be positioned to face east and west, following the layout shown in Fig. 2. The panels selected for this project are Canadian Solar panels with a power output of 580 W. Information obtained from the panel datasheet includes the panel width (130 cm) and the thickness of the aluminum frame (3.5 cm). The desired tilt angle for the panels is 20°, and a cleaning corridor width of 40 cm is necessary.

Fig. 8 illustrates the overhead perspective of the installed solar panels. The direct protection against lightning strikes is implemented using two levels, specifically levels 2 and 4 as outlined in Table 1.

The engineer will start the design of the panel steel layout to meet the direct lightning strike. The engineer utilizes the equations in this paper to determine the separation *DLew*. *Lg* is 0.3 m based on Eq. (6), this equates *Ls* to be 1.6 m. The separation *DLew* is found to be 4.9 m. Fig. 9 shows the system layout with all its dimensions. The feasibility of this basic assessment would have been unattainable without the incorporation of the equation presented in this paper. This aspect underscores the innovative and significant contribution of the proposed theoretical framework to the current literature of this domain. The simple demonstrates the ease of determining the dimensions of the steel structure by utilizing the proposed equations outlined in this paper. These equations can be integrated into software coding to facilitate swift and effective steel design for the installation of PV panels with east and west orientations.

In the theoretical setup, it has been noted that the installation of a standard lightning mast can impact the exposure of panels to sunlight.
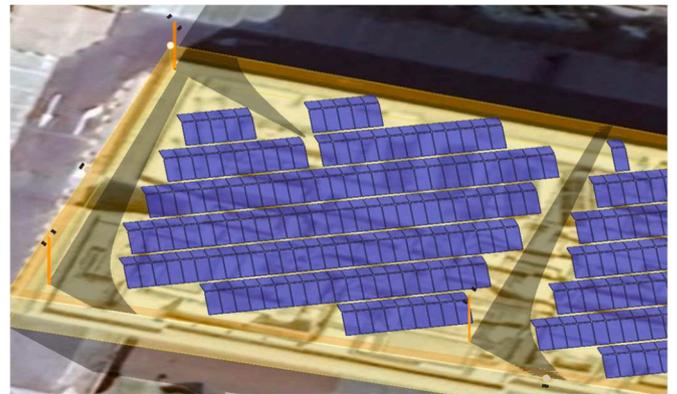

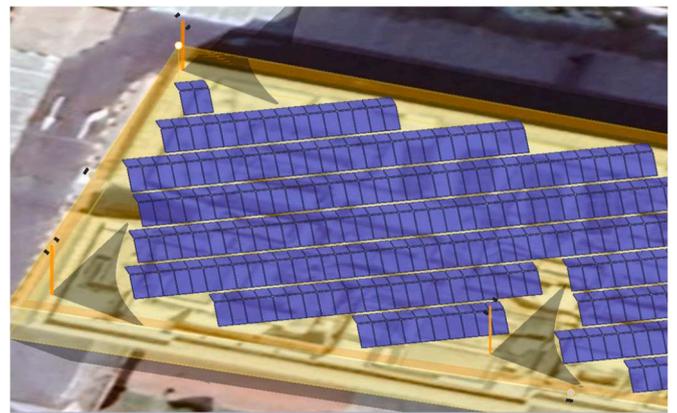
Fig. 10. Lightning masts shading on the panels.

Fig. 11. Shade due to lightning mast under different times of the day.

Additionally, placing a standard lightning mast in the configuration depicted in Figure 8 can lead to significant shading issues. Figs. 10 and 11 demonstrate the shading effects on the system when a vertical lightning rod is utilized. Figure 10 is based on a design that has no shading between 7:30am and 4:00pm, while Fig. 11 illustrates the shading impact on the panels if the shade-free period is reduced to between 9:00am and 3:00pm. Notably, positioning panels facing east and west can extend the generation period, with optimal sunlight exposure occurring when the sun is positioned in the east or west. Consequently, shading is anticipated from early morning to late afternoon. This highlights the importance of exploring alternative direct lightning protection methods that do not contribute to shading, thereby preserving system efficiency. The horizontal layout of lightning rods proposed in this paper is considered an innovative approach in light of these considerations.

It is worth noting that following the conventional approach outlined

in existing literature may result in persistent shading or a decrease in the number of panels. In larger systems, a single lightning mast may not offer adequate protection, necessitating the installation of multiple vertical lightning rods. However, this can lead to increased shading effects on the panels, diminishing system efficiency, lowering income generation, and raising the risk of hotspots. The utilization of large lightning masts results in thicker steel posts, thereby amplifying the shading effect on panels within the vertical mast layout. Increasing the number of vertical lightning masts to diminish their size could further intensify the shading impacts on the panels. Given that the primary aim of this paper is to introduce a novel horizontal lightning rod layout, the case study did not explore the comparison between various sizes of vertical masts and their shading effects, as this topic falls beyond the scope of the current research. It is also worth noting that for the proposed horizontal lightning rods, the size of the mast is fixed and doesn't change like the vertical masts.

5. Conclusions

Photovoltaic (PV) systems are increasingly integral to the electricity grid for their capacity to produce clean energy. The electrical performance of a PV system hinges on the level of solar radiation reaching the silicon cells in the panels. To optimize system output, it is imperative to ensure zero shading during sunlight hours. However, this requirement for unobstructed sunlight exposure also exposes the system to lightning strikes during storms. Conventional lightning protection measures, such as tall mast installations, often result in significant shading that diminishes panel efficiency. The innovative approach outlined in this paper aims to shield against direct lightning strikes without causing shading on the panels. By mitigating the risk of lightning strikes while minimizing shading effects, this method enhances system reliability and performance.

Moreover, the equations presented in the paper enable engineers to design an effective lightning protection system with minimal input required, such as information on the selected panels, panel orientations, and cleaning corridor width. The case study demonstrates that adhering to the guidelines outlined in the paper can lead to a reduction in the necessary investment for the earth grid, allowing for the proper steel layout of the panels to meet lightning protection standards without any shading. This innovative approach would not have been feasible without the introduction of the proposed layout and simplified equations developed through this research. Consequently, the paper offers significant advantages to the industry.

CRediT authorship contribution statement

Mohamad Nassereddine: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

We have no conflicts of interest to disclose.

Data availability

No data was used for the research described in the article.

References

[1] K. Padmanathan, U. Govindarajan, V.K. Ramachandaramurthy, B. Jeevarathinam, Integrating solar photovoltaic energy conversion systems into industrial and commercial electrical energy utilization—a survey, J. Ind. Inf. Integr. 10 (2018) 39–54.
[2] A.D. Adam, G. Apaydin, Grid connected solar photovoltaic system as a tool for green house gas emission reduction in Turkey, Renew. Sustain. Energy Rev. 53 (2016) 1086–1091.
[3] H. Satria, S. Syafii, A. Aswardi, Analysis of peak power capacity on rooftop solar PV 1.25 kWp at sun conditions 90 degrees, Int. J. Electr. Energy Power Syst. Eng. 4 (3) (2021) 173–178.
[4] A. Saleem, E.K. Mehmood, E.F. Rashid, The efficiency of solar PV system, in: Proceedings of 2nd International Multi-Disciplinary Conference 19, 2016, p. 20.
[5] G. Trzmiel, D. Głuchy, D. Kurz, The impact of shading on the exploitation of photovoltaic installations, Renew. Energy 153 (2020) 480–498.
[6] R.R. Hernandez, S.B. Easter, M.L. Murphy-Mariscal, F.T. Maestre, M. Tavassoli, E. B. Allen, C.W. Barrows, J. Belnap, R. Ochoa-Hueso, S. Ravi, M.F. Allen, Environmental impacts of utility-scale solar energy, Renew. Sustain. Energy Rev. 29 (2014) 766–779.
[7] N.H. Zaini, M.Z.A. Ab Kadir, M.A. Mohd Radzi, M. Izadi, N. Azis, N.I. Ahmad, M.S. M. Nasir, Lightning surge analysis on a large scale grid-connected solar photovoltaic system, Energies. (Basel) 10 (12) (2017) 2149.
[8] T.P. Chew, S.L.X. Xian, The impact of direct lightning strike damages on PV modules in a large Malaysian PV Farm, published in IEM J. 82 (2) (2021).
[9] M. Nassereddine, A. Hellany, Designing a lightning protection system using the rolling sphere method, in: 2009 S International Conference on Computer and Electrical Engineering 1, Ieee, 2009, pp. 502–506.
[10] IEEE Guide for Direct Lightning Stroke Shielding of Substations, IEEE 998-2012 Standard.
[11] J. Guo, X. Zhang, B. Wang, X. Hao, S. Zheng, Y.Z. Xie, A three-dimensional direct lightning strike model for lightning protection of the substation, IET Gen. Transm. Distrib. 15 (19) (2021) 2760–2772.
[12] M. Nassereddine, J. Rizk, G. Nasserddine, Soil resistivity structure and its implication on the pole grid resistance for transmission lines, Int. J. Electr. Comp. Eng. 7 (1) (2013) 41–45.
[13] A. Hellany, M.H. Nagrial, M. Nassereddine, J. Rizk, Soil resistivity structure and its implications on the earth grid of HV substation, World Acad. Sci. Eng. Technol. (2011) 1322–1326.
[14] IEEE guide for safety in AC substation grounding, IEEE 80-2013 standard.
[15] M.S.M. Nasir, M.Z.A. Ab-Kadir, M.A.M. Radzi, M. Izadi, N.I. Ahmad, N.H. Zaini, Lightning performance analysis of a rooftop grid-connected solar photovoltaic without external lightning protection system, PLoS ONE 14 (7) (2019) e0219326.
[16] N.I. Ahmad, M.Z.A. Ab-Kadir, M. Izadi, N. Azis, M.A.M. Radzi, N.H. Zaini, M.S. M. Nasir, Lightning protection on photovoltaic systems: a review on current and recommended practices, Renew. Sustain. Energy Rev. 82 (2018) 1611–1619.
[17] N. Fallah, C. Gomes, M.Z.A. Ab Kadir, G. Nourirad, M. Baojahmadi, Lightning protection techniques for roof-top PV systems, in: 2013 IEEE 7th International Power Engineering and Optimization Conference (PEOCO), IEEE, 2013, pp. 417–421.
[18] Y. Zhang, H. Chen, Y. Du, Lightning protection design of solar photovoltaic systems: methodology and guidelines, Electr. Power Syst. Res. 174 (2019) 105877.
[19] N.H. Zaini, M.Z.A. Ab-Kadir, M. Izadi, N.I. Ahmad, M.M. Radzi, N. Azis, W. W. Hasan, On the effect of lightning on a solar photovoltaic system, in: 2016 33rd International Conference on Lightning Protection (ICLP), IEEE, 2016, pp. 1–4.
[20] Z. Mohammed, H. Hizam, C. Gomes, Lightning strike impacts on hybrid photovoltaic-wind systems, Indon. J. Electr. Eng. Comp. Sci. 8 (1) (2017) 115–121.
[21] T. Khatib, R. Deria, East-west oriented photovoltaic power systems: model, benefits and technical evaluation, Energy Convers. Manage. 266 (2022) 115810.
[22] E. Pons, R. Tommasini, Lightning protection of PV systems, in: 2013 4th International Youth Conference on Energy (IYCE), IEEE, 2013, pp. 1–5.
[23] I. Hetita, A.S. Zalhaf, D.E.A. Mansour, Y. Han, P. Yang, C. Wang, Modeling and protection of photovoltaic systems during lightning strikes: a review, Renew. Energy 184 (2022) 134–148.
[24] C.A. Christodoulou, L. Ekonomou, I.F. Gonos, N.P. Papanikolaou, Lightning protection of PV systems, Energy Syst. 7 (2016) 469–482.
[25] C. Christodoulou, V. Kontargyri, K. Damianaki, A. Kyritsis, I. Gonos, N. Papanikolaou, Lightning performance study for photovoltaic systems, in: 19th International Symposium on High Voltage Engineering, Pilsen. Czech Republic, 2015.
[26] X.X. Lee, P.C. Thum, Lightning Shielding with Shading Avoidance for a Photovoltaic (PV) Farm, J. Instit. Eng. Malaysia 83 (1) (2022).
[27] K. Sobolewski, E. Sobieska, Analysis of the effectiveness of lightning and surge protection in a large solar farm, Arch. Electr. Eng. 71 (2) (2022).
[28] X.X. Lee, P.C. Thum, The Impact of Direct Lightning Strike Damages on PV Modules in a Large Malaysian PV Farm, J. Instit. Eng. Malaysia 82 (2) (2021).
[29] S. Vaca-Jiménez, C. Morales, F. Ordóñez, Improvements of photovoltaic systems by using solar tracking in equatorial regions, in: Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands, 2017, pp. 25–29.
[30] Lightning protection, Australian standard for lightning protection, AS/NZ (1768) 2021.
[31] B.M. Kouchaki, M.L. Bernhardt-Barry, C.M. Wood, T. Moody, A laboratory investigation of factors influencing the electrical resistivity of different soil types, Geotech. Testing J. 42 (4) (2019) 829–853.
[32] J. Cao, Y. Du, Y. Ding, R. Qi, B. Li, M. Chen, Z. Li, Practical schemes on lightning energy suppression in arresters for transformers on 10 kV overhead distribution lines, IEEE Trans. Power Deliv. 37 (5) (2022) 4272–4281.
[33] IEEE Guide for Measuring Earth Resistivity, Ground impedance, and earth surface potentials of a grounding system, IEEE Standard 81–2012.
[34] Protection against lightning; Part 3: damage to structures and life hazard, IEC Standard (2011) 62305. –3.