LIGHTNING SHIELDING WITH SHADING AVOIDANCE FOR A PHOTOVOLTAIC (PV) FARM

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ABSTRACT

The special requirement of a PV farm lightning shielding system is that it should not introduce shadow on the active PV surfaces so as to avoid impaired PV generation output. By using a simple, repeatable-unit PV row made up of single or multiple PV strings, the problem of finding a cost-effective and efficient PV row lightning finial arrangement can be resolved. The shading analysis combined with the MS IEC 62305 implementation of the Rolling Sphere Method (RSM) is able to give a simple procedure that lends itself to spreadsheet calculations pertaining to PV farm lightning shielding design.

Keywords: Core Shadow, Lightning Air Termination, Shading Avoidance

1.0 INTRODUCTION

Unlike traditional lightning protection approaches, the special requirement of a PV farm lightning shielding system is that it should not introduce shadow on active PV surfaces so as to avoid impaired PV generation output. While sophisticated software programs are now available for the analysis of air termination systems, what is lacking is for shading analysis to be built into the same program to handle the PV shading problem concurrently. A PV farm is built-up of many PV rows. By using a simple, repeatable-unit PV row made up of single or multiple PV strings, the problem of finding a cost-effective and efficient PV row air termination system is simplified.

The purpose of this paper is to present a simplified and robust method of determining lightning finial arrangement on a PV row taking into account the shading effect that is introduced by its finial core shadow (umbra) at certain times of the day. First, it addresses the core shadow formation then does the shadow analysis to determine inter-row separation for shading avoidance. With inter-row separation and row pitch (inter-row spacing) determined, it proceeds with the RSM to determine the finial length and finial spacing on the PV row. Because the whole analysis could be done on a unit PV row basis, it lends itself to be repeated over the PV farm. Its simplicity also lends itself to spreadsheet implementation.

2.0 STRUCTURE OF THE PV FARM

The PV farm structure is characterised by an extensive low-height and isolated-surface area. It physically resembles a shielded open-structure since the PV module perimeters are made of aluminium frames that are bonded and earthed in each string/row arrangement. Most stroke terminations are characterized by overhead downward flashes with little or no side stroke terminations because of the PV row's low height. There are generally, 2 ways of providing lightning shielding. The first is by adding external steel finials to the natural component LPS. The second makes use of the available PV module aluminium frames as natural air termination in an effort to save cost. Cost-saving considerations also compel the natural components of the PV module support structure and foundations to be used as the LPS down-conductor system and earthing system as shown in Figure 1.

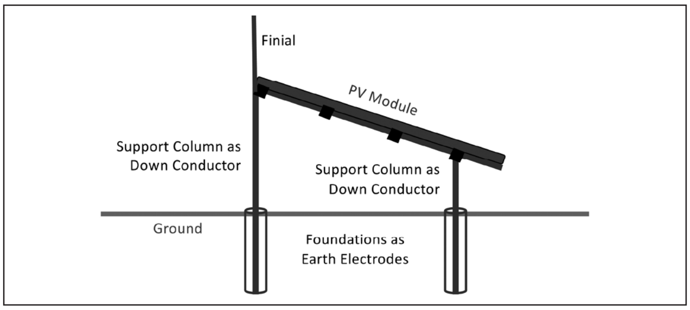

Figure 1: PV Module Support Structure Acting as LPS

In most cases, the aluminium frames are not inherently designed or intended as air terminations. They do get damaged by hotspot punctures at the point of stroke attachment. A more satisfactory engineering solution may be achieved by adding to the natural-component LPS, steel finials arranged on the ridge of the inclined PV row [1]. Their role is to preferentially intercept lightning strokes while the aluminium mesh's role is relegated to the screening and current distribution functions. With such a method, the PV string shielding failure is determined by finial height and finial positioning/spacing.

3.0 SHADING FROM AIR TERMINATIONS

If air terminations are provided for lightning protection, they may present dynamic shading impacts to the active PV surfaces on which their shadows fall [2]. Dynamic shading possibility depends on the core shadow (umbra) length formed by opaque above-PV-surface objects in accordance to the sun's elevation and direction. The space beyond the core shadow exhibits a diffuse shadow from its penumbra which presents less impact on PV module output. Thus, air termination must be placed such that their core shadows do not fall on active PV surfaces. There are 2 types of air terminations, namely the tall mast and the short finials. The following section evaluates their possible applications in the PV farm.

3.1 Core Shadow Formation with the Umbra

In practical situations, only umbra shadows are assumed to have significant shading impacts on PV surfaces. In contrast, penumbras produce weak shading intensities. A simple shadow analysis is made here to determine the core shadow transitions of narrow/thin to wide vertical objects. In general, umbra shadow formation depends on 3 factors, namely :-

1. The length of the object's umbra is taken to be proportional to its width, e.g. for a finial of diameter, d_f, , its umbra length, L_u formed in space is fixed at 108 x d_f as shown in Figure 2a. The constant is the ratio of the sun's distance from Earth and the sun's diameter [3, 4].
2. The sun's elevation angle, α above the horizon determines the umbra's inclination.
3. The height, H of the object above the ground to produce an inclined umbra layer and surrounded by its penumbra in space; the thickness of the umbra above the ground is determined by the object's height. A shadow is formed on the ground if this inclined but length- and thickness-limited umbra layer intersects the ground.

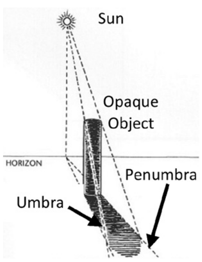

Figure 2a: Vertical Rod's Umbra and Penumbra Illustrated

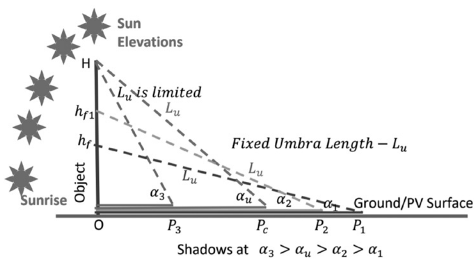

Figure 2b: Shadow Formation with Vertical Object

Figure 2b illustrates how shadow is formed as the sun rises. When the sun's elevation angle, α is zero, there is no umbra intersection with the ground because the umbra volume lies just above the ground plane and no shadow is formed. As the sun rises low in the horizon, the full umbra length, L_u initially forms the shadow at a small elevation angle, α_1. While the umbra's lower region intersects the ground plane at full umbra length, L_u, its upper volume still lies in the space above the ground. It contributes partially to the shadow OP_1 on the ground. The shading intensity is weak. As the sun rises, α increases to α_2. The umbra length, L_u inclines and forms its shadow, OP_2 on the ground as shown in Figure 2b. Its intensity increases. In general, the shadow length,

$$L_s = L_u.\cos\alpha \qquad \text{where } \alpha < \alpha_u \tag{1}$$

This continues until the shadow length is OP_c at sun elevation angle α_u. This critical angle defines the height on the object ($h_f = H$) that produces the full umbra length, L_u just touching the ground. At greater heights, the umbra length produced is too short to touch the ground. Thus, angle, $\alpha_u = sin^{-1}\left(\frac{H}{L_u}\right)$ and the shadow geometry makes a transition at H = L_u.

When the sun rises beyond this elevation angle at say, $\alpha_3 > \alpha_u$, the ground-intersecting umbras are formed by the object's surface at heights less than H. The shadow length, OP_3 is hence, fixed by H. The shading intensity is high but the shadow length, L_s is given by :-

$$L_s = H/\tan\alpha \qquad \text{where } \alpha \geq \alpha_u \tag{2}$$

If the width of an object is 1 metre, L_u will be 108m. If the object's physical height is shorter, then its umbra-limit angle, α_u is small. Its L_{u-} transition will occur a short while after sunrise with a long shadow. In contrast, a thin blunt-tipped finial with short umbra length will have its umbra-limited angle, α_u at 90°; its shadow is umbra-length limited with no transition.

3.2 Shadow Analysis

Table 1 shows the calculated shadow lengths on the ground surface of a tall mast and of a short blunt-tipped finial. Within the practical range of finial diameters (8mm to 16mm), the umbra length ranges from 0.86m to 1.73m. A 14 mm diameter finial is selected for comparison with a typical 150mm diameter lightning mast of height 6.5m. The umbra-limited angle, α_u for both air terminations exceeds 20°. Equation (1) is appropriate to be used in the just-after-sunrise shading analysis. But compared with the finial, the mast length transits to Equation (2) after 23.66°.

For any PV farm location, the time of allowable umbra shading has to be limited to the early hours of the morning and late hours of the evening. This time should be specified so that an object's core shadow does not produce adverse impact on PV generation output. In practice, it could lie between 7.30am and 8.30am such that the finial's shadow cast by the sun is short and it will not fall on any active PV surface at times later.

Table 1 shows that the mast's shadow length on the ground is much longer than that of the finial. At a sun elevation angle of 30°, a 6.5m lightning mast requires a shading clearance of 11.258m on the ground as compared to 1.309m for a short finial. The shorter finial shading clearance may be allowed to fall in the PV inter-row separation space. Thus, shading impact is easier to mitigate with the multiple finial solution than the single tall-mast solution. The former resolves the problem at the PV row level while the latter needs 8.6 times larger shading clearance on the PV farm ground.

Table 1: Comparison of Mast and Finial Shadow Lengths

	Mast	Finial
Height, m	6.50	2.50
Diameter, mm	150.0	14.0
Fixed Umbra Length, m	16.200	1.512
Umbra-Limited Angle, °	23.66	90.00
Sun's Elevation, °	**Shadow Length, m**	
	Mast	**Finial**
5.0	16.138	1.506
10.0	15.954	1.489
20.0	15.223	1.421
30.0	11.258	1.309
45.0	6.500	1.069
60.0	3.753	0.756
80.0	1.146	0.263

4.0 SHADING AVOIDANCE OF FINIALS MOUNTED ON PV ROWS

If multiple finials are opted for lightning shielding at the PV row level, their effectiveness is determined by their vertical length and the spacing between them. Usually, one or more inclined PV strings are grouped to form a PV row. The finials are mounted along the row's ridge (as shown in Figures 1 and 5) and at the high corners. Apart from other considerations, the rows should be orientated such that finial shadows do not fall on neighbouring rows.

4.1 Sun Direction and PV Row Orientation

The formation of shadows depends on the sun's position in the sky and the time-of-day. Its position is defined by its elevation angle, α and its azimuth, Ψ as shown in Figure 3a. The sun's elevation determines an object's projected shadow length while its azimuth determines the shadow's direction relative to a PV row's orientation azimuth; both azimuths by convention are referenced to the North. The sun's azimuth angle may be calculated from either [5] or [6].

The sun's positions in the sky over one full year can be represented in a 2-D Cartesian chart for a specific location on the Earth's surface. Figure 3b shows the sun's path at location P Latitude 3.1°(north of the Equator), Longitude 101°(in Peninsular Malaysia). It can be used to orientate the PV row to avoid shading as well as to optimise generation output. Based on Figure 3b, PV operation considerations may adopt a 30° sun's elevation corresponding to 8.00am and a 120° azimuth angle, A.

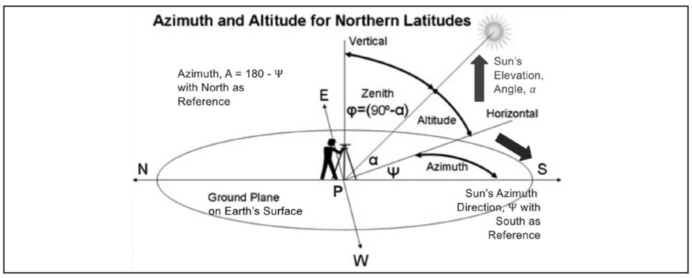

Figure 3a: The Sun's Angles with Reference to Northern Latitudes

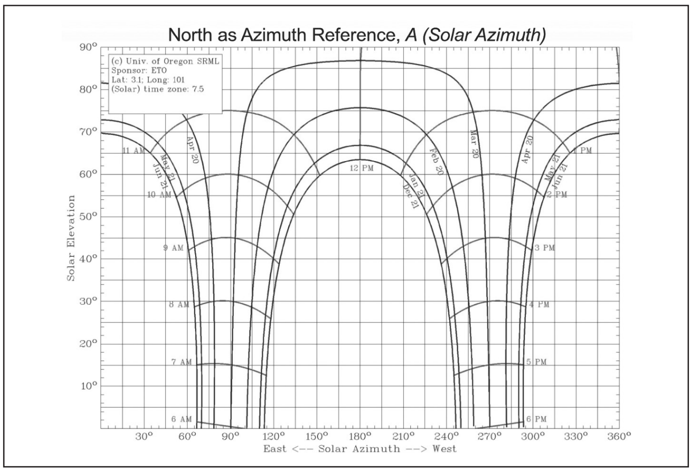

Figure 3b:University of Oregon 2-D Sun Path Chart for Latitude 3.1° and Longitude 101° [7]

4.2 Shadow Length and Shading Avoidance

For low shading impact, a finial has to be short and thin. It's length is determined from shading analysis and its diameter must satisfy Table 6 requirements of MS IEC 62305-3 [8].

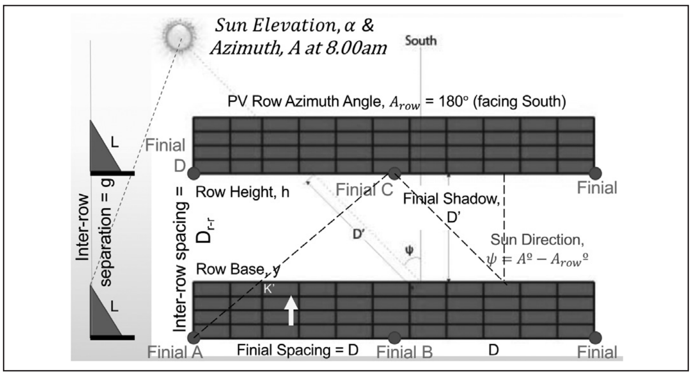

Figure 4: Plan View - Sun Direction and PV Row Orientation

Figure 4 is used to obtain the PV inter-row separation, g. Table 1 gives the umbra length, L_u = 1.512m. For the sun elevation angle, α = 30°, the shadow length, L_s = D' = L_u.cos 30° = 1.309m.

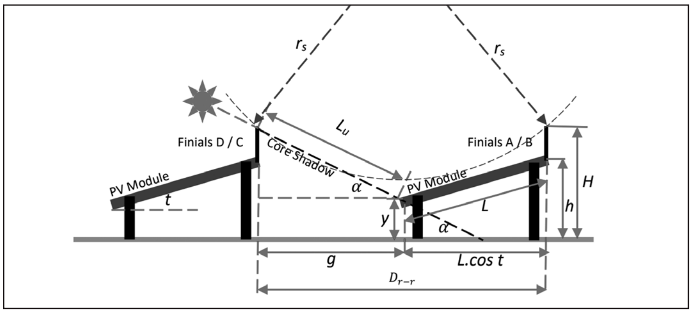

Figure 5: D_{r-r} Elevation View of 2 PV Rows with Finials Showing Row Pitch and Rolling Sphere

The PV row is usually orientated facing South-east to South at azimuth angle, A_{row} between 150° and 180°. The South-east orientation angle (150°) gives a larger shadow length. ψ as shown in Figure 3a, is given by

$$\psi = A - A_{row} \quad (3)$$
$$= 120° - 150°$$
$$= -30°$$

From Figures 4 and 5, the PV inter-row separation, g, is given by

$$g = D'.\cos\psi \quad (4)$$
$$= 1.309 \cos(-30°)$$
$$= 1.134\text{m}$$

Thus, to avoid shading for a PV row orientated in the 150° (south-east) direction, the inter-row separation must be at least 1.134m. If the row is orientated to face the sun at which $\psi = 0°$, the inter-row separation for 8.00am at location P is then 1.309m. The PV inter-row separation is normally used as an access way for construction, operation and maintenance. As such, g has a minimum width which generally is 1.0m. In this case, g is larger than 1.0m, hence shading avoidance take precedence with g increased to 1.134m.

For a given row's inclined width, L on the PV module surface and tilted at an angle of t°, the row spacing or pitch, $D_{r\text{-}r}$ as shown in Figures 4 and 5, is given by

$$D_{r\text{-}r} = g + L.\cos t \quad (5)$$

Hence, if L is 4m and the PV row's tilt angle is 10°, the row pitch, $D_{r\text{-}r}$ is 5.073m.

5.0 LIGHTNING RSM SHIELDING ANALYSIS

The purpose of lightning shielding is to position equal-height finials on the PV row's ridge in relation to neighbouring PV rows so that they prevent direct lightning strikes to the PV modules. The MS IEC 62305 rolling sphere method [9] is employed in the analysis to find the finial length, L_f and finial spacing, D such that a group of finials can prevent a rolling sphere from coming into contact with the inclined PV module surface.

The relevant shielding geometry is depicted in Figure 4 with 4 finials placed at the corners of a rectangular block having ground length, D and ground width, $D_{r\text{-}r}$. The length of the diagonal on the ground plane is $D_d = \sqrt{D^2 + D_{r-r}^2}$. D_d is depicted along the block's A-C section view in Figure 6. The rolling sphere radius, rs is calculated from the minimum interception stroke current, *I* in kA based on the desired probability of shielding. It is given in MS IEC 62305 [9] as

$$r_s = 10I^{0.65} \quad (6)$$

Based on a given design interception current, the penetration depth, p of the greater circle of the rolling sphere into the block ABCD is as follows:-

$$p = r_s - \sqrt{r_s^2 - 0.25D_d^2} = r_s - \sqrt{r_s^2 - 0.25(D^2 + D_{r-r}^2)} \quad (7)$$

For real application of the expression, D_d has to be limited by the condition: $0.5D_d < r_s$.

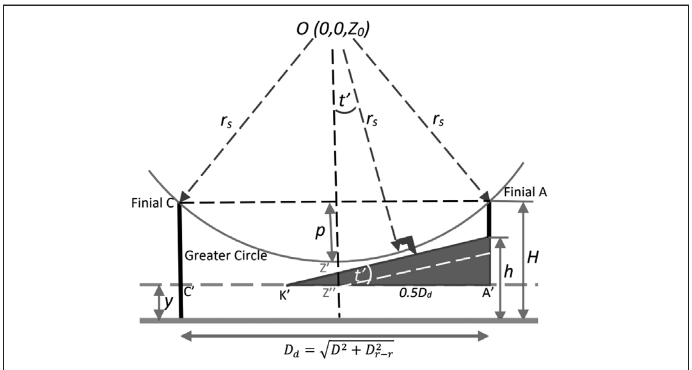

Figure 6: A-C-C'-A' (D_d) Vertical Plane Containing Rolling Sphere

5.1 Finial Length Analysis for Sphere Rolling Over the PV Row's Ridge

By substituting D_d with D into the p expression, the finial length, L_f on the D-section of the block containing the PV row's horizontal ridge can be evaluated by $r_s - \sqrt{r_s^2 - 0.25D^2}$.

For inclined surfaces of the block, their required finial lengths are derived in the Appendix.

6.0 DIMENSIONS OF FINIAL SYSTEM

Figure 7 illustrates the manner in which the finial length and spacing are determined for a representative 30m long PV row in Malaysia. Typically in Malaysia, the tilt angle, α of the PV row is around 10°. The PV row may at the extreme, face South-east (ψ=-30) for which the inter-row separation, g is taken to be 1.309m. For a PV inclined surface width, L of 4m, a row pitch, $D_{r\text{-}r}$ of 5.073m is required. The height of the PV row's ridge, *h-y* is 0.695 m. Along the PV row's ridge, a number of finials can be provided depending on the cost and the desired interception efficiency of the finial system.

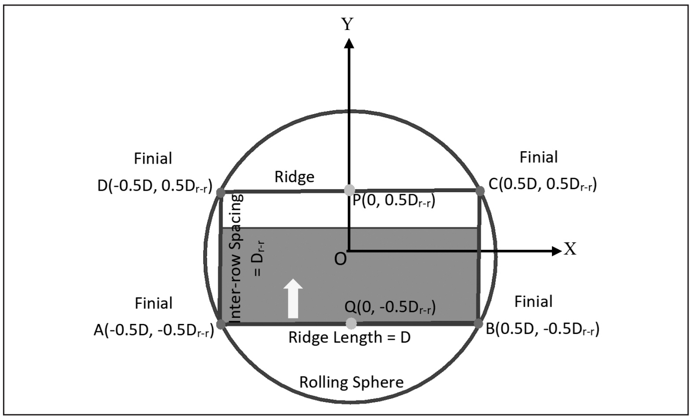

Figure 7: Plan View of Rectangular Block ABCD with Rolling Sphere

For inclined surfaces, the rolling sphere is shown in Figure 7. The finial length calculations are implemented in a spreadsheet. Table 2 summarises the finial length results from the analysis of various row sections for various finial spacings. The PV row's ridge requires the longest finial length because it presents the largest lightning exposure whereas the D_d and the $D_{r\text{-}r}$ planes are generally less exposed due to the row's inclination. Thus, it seems that in this case, the finial length of a PV row is determined by its ridge.

Table 2: Finial Lengths for Various Finial Spacings With PV Row Orientated at 150° Azimuth

PV Row Length, m	30.00	Finial Length, m			
No. of Equal Finial Sections per Row	Finial Spacing, D m	$D_{r\text{-}r}$ Plane	D_d Plane	Row's Ridge	PV Row
1	30.000	0.000	6.358	6.563	6.563
2	15.000	0.000	1.182	1.427	1.427
3	10.000	0.000	0.402	0.621	0.621
4	7.500	0.000	0.160	0.347	0.347

Table 2 also shows that the minimum finial length required varies quite substantially with finial spacing. If a row is a single section, the finial length at the ends of the row will have to exceed 6.563m; a height equivalent to that of a single tall mast. As deduced from Table 1, it does not have a shading clearance advantage. Neither does it have a land-use and cost advantage. Design and construction considerations favour the multi-section options of either 2, 3 or 4 equal sections per row. The final selection depends on design optimisation and cost.

Since the PV row's ridge will attract a large number of lightning terminations, it is necessary to examine the impact of shorter finial lengths on the ridge's lightning exposure whose expression is derived in the Appendix. Table 3 shows that reduction in length incurs larger ridge exposures. Hence, finial lengths must always be adequately provided.

Table 3: Impact of Compromised Finial Length on PV Row's Ridge Lightning Exposure

Finial Spacing, D m	15.0	10.0	7.5
Row Finial Length, L_f m	1.427	0.621	0.347
Dd Finial Length, l m	1.182	0.402	0.160
% Finial Short, $100(1-l/L_f)$	17.14	35.28	53.84
Ridge Exposure, D_e m	6.303	5.969	5.514
% Exposure, 100. D_e/D	42.02	59.69	73.52

Table 4 compares the finial lengths on the basis of finial spacing, PV row orientation and interception current. For a given interception current, the finial length does not change with PV row orientation azimuth. This consistency confirms that lightning exposure is independent of row orientation.

Table 4: Finial Length Comparison for Two PV Row Orientations and Three Interception Currents

Interception Current/ Probability*/ Striking Distance	3 kA / 99.0% / 20.42m		2.5 kA /99.2% / 18.14m		2 kA / 99.5%/ 15.69m	
Azimuth, °	150	180	150	180	150	180
No. of Sections/ (Finial Spacing)	Min. Finial Length, m		Min. Finial Length, m		Min. Finial Length, m	
2 /(15m)	1.427	1.427	1.623	1.623	1.908	1.908
3 /(10m)	0.621	0.621	0.703	0.703	0.818	0.818
4/(7.5m)	0.347	0.347	0.392	0.392	0.455	0.455

*Note: * - Probability of the interception current being exceeded.*

It is noted that a 15m section requires a taller finial, (greater than 1m) compared to a 10m section. If the finial length is to be less than 1m, the suitable finial spacings are between 7.5m to 10m. In this range, the finial mounting and connection to their support structure as shown in Figure 1, may have to be evaluated with costs for the selection of finial spacing and length.

A more significant change in finial length comes from the change in the interception current. A lower design interception current with higher exceedance probability will achieve a higher finial interception efficiency because the greater stroke currents would not penetrate the shielding system. While MS IEC 62305-1 [9] suggests a 99% efficiency with a 3 kA design current for LPL I, a 2 kA design current can give 99.5% interception efficiency. In terms of overall performance, construction and quantity of materials used, the 2 shorter sections only require standard finial lengths in the range of 0.5m to 1.0m which is less than L_u (= 1.512m from Table 1) to achieve the required interception efficiency as suggested in [1].

7.0 CONCLUSION

Shadow formation analysis suggests that between a short finial and a tall mast, shading avoidance in a PV farm is better achieved with multiple short finials than single tall masts. The former resolves the problem at the PV string/row level while the latter needs a larger surrounding shading clearance area. In order for finials not to create significant shading impact, the pitch between PV rows must be sufficient so that the finial's core shadow will not encroach into the neighbouring rows. This core shadow length is a function of the sun's elevation and azimuth and the row's orientation and tilt angle. It is shorter than that of a tall mast and may be designed to fall within the inter-row separation space.

The expression for the height and length of a finial with respect to inter-finial spacing for an inclined PV row surface is derived using the RSM. Investigation with the range of finial lengths is made with inter-finial spacings that are likely to be encountered in practice. The finial design procedure also examines the impact on PV row's ridge lightning exposure as a result of shorter finial lengths. It concludes that finial lengths must always be adequately provided. Technical comparison points to simple short finials of 0.5m to 1.0m in length which is less than its umbra length. It leads to the prospect of a multi-section design for a 30m PV row. For cost-effectiveness in practice, the PV row may be divided into 2, 3 or 4 equal sections. A simple approach for the implementation of lightning shielding system with shading avoidance for a PV farm is demonstrated. Its calculation can be easily made with a spreadsheet. ■

APPENDIX - DETERMINING FINIAL LENGTHS

A.1 The Coordinate of the Centre of the Rolling Sphere, O(0, 0, Z0)

In order to prevent the circle in Figure 6 from touching the inclined PV module surface, the finials' minimum protruded length for a given PV row height, h and a tilt angle, *t* is determined geometrically. The height of the PV row's ridge is

$$h\text{-}y = L.\sin t \tag{A1}$$

Applying the Similar Right Angle Triangle Theorem to the ratio of sides in Figures 4 and 6,

$$\frac{A'K'}{L.\cos t} = \frac{D_d}{D_{r-r}} \text{ giving } A'K' = \frac{D_d}{D_{r-r}}.L.\cos t \tag{A2}$$

and from Figure 6, the diagonal tilt angle, t' is given by

$$tan\ t' = \frac{h-y}{A'K'} = \frac{(h-y).D_{r-r}}{D_d.L.\cos t} = \frac{D_{r-r}}{D_d} tan\ t \quad (A3)$$

$$\text{and } \sec t' = \sqrt{1 + \left(\frac{D_{r-r}}{D_d}\right)^2 tan^2 t} \quad (A4)$$

The angle t' reaches a physical maximum when the rolling sphere circle touches the PV row's ridge. Its maximum is given by

$$sin\ t'_{max} = \frac{D_d}{2r_s}$$

$$\text{or } t'_{max} = sin^{-1}\left(\frac{D_d}{2r_s}\right) \quad (A5)$$

Beyond it, the sphere rolls over the PV row's ridge. Thus, the analysis of Figure 6 A-C plane is made with $t' < t'_{max}$.

The diagonal plane A-C-C'-A' in Figure 6 is treated as an X-Z plane. Applying coordinate geometry to the plane, the gradient and intersect of the inclined PV surface line are :-

Line's gradient = *tan t'*

Its fixed intersect at X = 0 with the Z-axis, $Z'Z'' = (h-y) - 0.5D_d.tan\ t' = (h-y) - 0.5D_{r-r}.tan\ t$

$$\text{The vertical length } OZ' = r_s.sec\ t' = r_s.\sqrt{1 + \left(\frac{D_{r-r}}{D_d}\right)^2 tan^2 t} \quad (A6)$$

Thus, the Z-coordinate of centre, O of the rolling sphere is :-

$$Z_0 = OZ' + Z'Z'' = r_s.\sqrt{1 + \left(\frac{D_{r-r}}{D_d}\right)^2 tan^2 t} + (h-y) - 0.5D_{r-r}.tan\ t \quad (A7)$$

A.2 Sphere Sitting on top of the Block ABCD

The equation of the rolling sphere whose plan view is depicted in Figure 7, is

$$(Z - Z_0)^2 + Y^2 + X^2 = r_s^2$$

$$Z = H - y = Z_0 \pm \sqrt{r_s^2 - X^2 - Y^2} \quad (A8)$$

The RSM is being applied to the ABCD rectangular section which has its mid-point below the rolling sphere's centre O and its corners A, B, C and D. For $H\text{-}y < Z_0$ and $0 \le t' < t'_{max}$,

$$H - h = r_s.\sqrt{1 + \left(\frac{D_{r-r}}{D_d}\right)^2 tan^2 t} - 0.5D_{r-r}.tan\ t - \sqrt{r_s^2 - X^2 - Y^2} \quad (A9)$$

Thus, for a given a striking distance, the finial length depends on the finial spacing, the PV row pitch and its tilt angle.

For example, if the coordinate of the finial at corner A is $(-0.5D, -0.5D_{r-r}, H\text{-}y)$, finial A's length,

$$L_f = H - h = r_s.\sqrt{1 + \left(\frac{D_{r-r}}{D_d}\right)^2 tan^2 t} - 0.5D_{r-r}.tan\ t - \sqrt{r_s^2 - 0.25D^2 - 0.25D_{r-r}^2}.$$

Symmetry ensures the 3 other corners B, C and D have the same finial length as A.

In the case of $t' \ge t'_{max'}$, $L_f = 0$ implying that the PV row's ridge is a natural air termination. However, for reasons given in [1], the PV module's thin aluminium frame should not be used. Hence, the need for extraneous finials on the ridge at corners A, B, C and D.

A.3 Sphere Rolling along the Ridges of Planes AB and CD from BC to AD

Based on Figure 5, the finial length can also be evaluated for the D_{r-r} section in which case,

$$L_f = r_s.sec\ t - 0.5D_{r-r}.tan\ t - \sqrt{r_s^2 - 0.25D_{r-r}^2} \quad (A10)$$

which is valid for $0 \le t < t_{max}$. Similarly, in the case of $t \ge t_{max} = sin^{-1}\left(\frac{D_{r-r}}{2r_s}\right)$, $L_f = 0$. Lightning shielding is naturally provided by the PV row's ridge at corners A, B, C and D.

A.4 Sphere Rolling Over PV Row's Ridges of Planes AB and CD

In the vertical planes AB and CD that contain the finial spacing *D*, the finial length, L_f is determined from its sphere rolling over the ridge with penetration depth given by

$$p = L_f = r_s - \sqrt{r_s^2 - 0.25D^2} \quad (A11)$$

A.5 Ridge Exposure due to Shortened Finial Length

Being the highest line on the PV row, the ridge has a higher probability of stroke attachment. If the finial length is compromised with $l_f (< L_f)$, then the rolling sphere surface will intersect the ridge and expose it to lightning attachments. By RSM according to [8], the exposure length is

$$D_e = 2\sqrt{r_s^2 - (r_s - l_f)^2} \quad (A12)$$

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