App. Math. and Comp. Intel., Vol. 2 (1) (2013) 109–120

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Lightning protection for roof-mounted solar cell using two masts

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Received: 13 February 2012; Revised: 18 February 2013, Accepted: 20 February 2013

Abstract: *Houses invested in roof-mounted solar cell need protection from direct lightning. This paper presents the application of numerical method in designing the height and location of masts based on protection angle method according to international standard IEC 62305. An isolated external lightning protection system using two masts is designed. The protected zone which is in the volume according to the protection angle method, depends on the protection level, the rolling sphere radius and the height of the masts which must be less than the rolling sphere radius defined in IEC standard. Furthermore, separation distance between the protected house and mast depends on the height of the mast. This paper develops a program using heuristic numerical method to design masts to protect a house with roof-mounted solar cell. Input data such as the house dimensions and the lightning protection class should be provided. This program is tested on houses with different dimensions. The height and location of two masts are obtained. The numerical results show that this program can be used effectively and correctly.*

Keywords: *Heuristic numerical method, Lightning protection, Mast, Roof-mounted solar cell*

PACS: *89.20.Kk, 02.60.-x*

1 Introduction

Houses invested in roof-mounted solar cell may expose to direct lightning. Protection physical damage to structures and living beings against lightning should comply with international standard IEC 62305 [1]. Photovoltaic (PV) structures on the roof are the highest point exposing to lightning stroke. A PV system must be bonded to ground to reduce shock and fire hazards [2]. Additional down conductors and ground rods must be provided. Inappropriate air terminals may not protect structures [3]. Consequently, concrete on a roof may be damaged and its debris is hazardous to people and property below. Lightning protection system (LPS) with round grounding is installed to protect the house using solar and wind energy [4]. A direct lightning strike to a house roof may

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occur [5]. This type of strike is very rare. However, it could cause severe damage the structure and most of electronic equipment in the house. LPS with air terminal installed on the roof, down conductors and buried ground electrode is suggested [5].

An isolated external lightning protection system (LPS) is used to avoid the thermal and explosive effects at the striking point which may cause damage to solar cell panels. LPS for roof-mounted solar cell should use isolated masts [6], [7]. Lightning rods are installed to protect outdoor solar cell arrays from lightning stroke [4].

There are four classes of LPS depending on lightning protection level defined in IEC 62305-1. LPS class III should be used for solar cell protection [7]. An isolated LPS comprises air termination mast and earth termination system. This paper designs only the height and location of masts. Heuristic numerical method (HNM) is proposed to calculate for the minimum height of air terminal masts while satisfying various constraints such as protection zone, separation distance. HNM is tested on houses with different sizes.

The organization of this paper is as follows. Section 2 addresses the problem formulation. The HNM algorithms are described in Section 3. Numerical results are presented in Section 4. Discussion is given in Section 5. Finally, the conclusion is concluded.

2 Problem formulation

2.1 Lightning protection

LPS could be designed by three methods: rolling sphere, protection angle and mesh. Protection angle method is suitable for a simple shape structure, thus it is used in this paper to protect a house with roof-mounted solar cell. Protective angle depends on the height of mast and the protection class as shown in Figure 1. The protective angles for all classes must be more than 25^{o}.

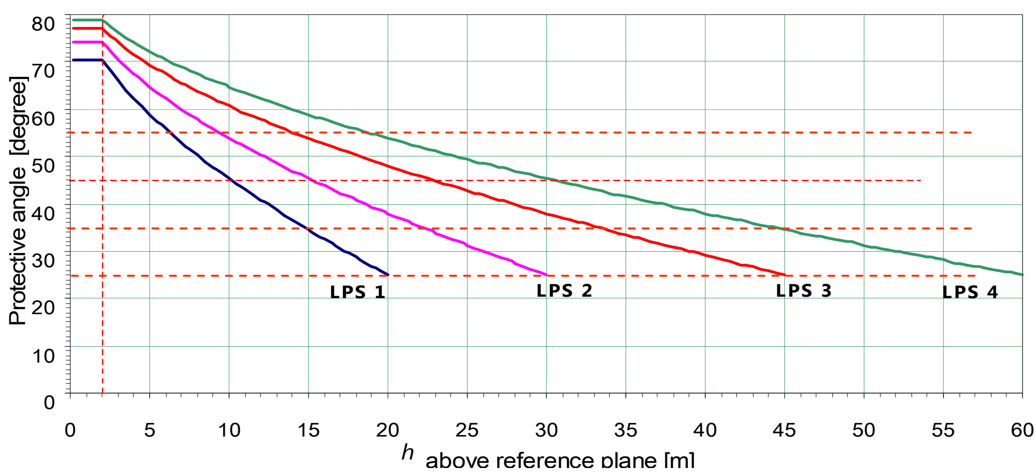

Figure 1: Protective angle [8]

In [8] the equation (1) is used to approximate the value of protective angle corresponding to Figure 1 whereas the rolling sphere radiuses for each LPS class are shown in Table 1. The protective angle and the corresponding protected volume are shown in Figure 2.

$$\alpha = \sin^{-1}(1 - \frac{h_{mast}}{\sqrt{3} \cdot R}) \quad (1)$$

α : protective angle

h_{mast} :height of the mast(m)

R : rolling sphere radius (m)

Table 1: The rolling sphere radius for each LPS class [1]

LPS class	I	II	III	IV
Rolling sphere radius (m)	20	30	45	60

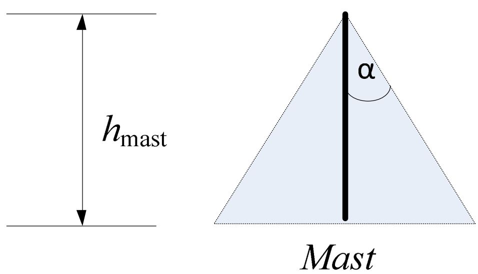

Figure 2: Protective angle [8]

2.2 Lightning protection with two masts

At least two masts should be used in LPS for a house with roof-mounted solar cell [6]. LPS using two masts to protect a structure is shown in Figure 3. The top view protected zone shown in Figure 4 is corresponded to protective angle, α_2, using ground as reference. The house is mainly protected by α_1. However, the protective cone corresponding to α_2 should cover the house as shown in Figure 4. Furthermore, the protective cone corresponding to α_1 should cover the house at point b, the outermost point as shown in Figure 5.

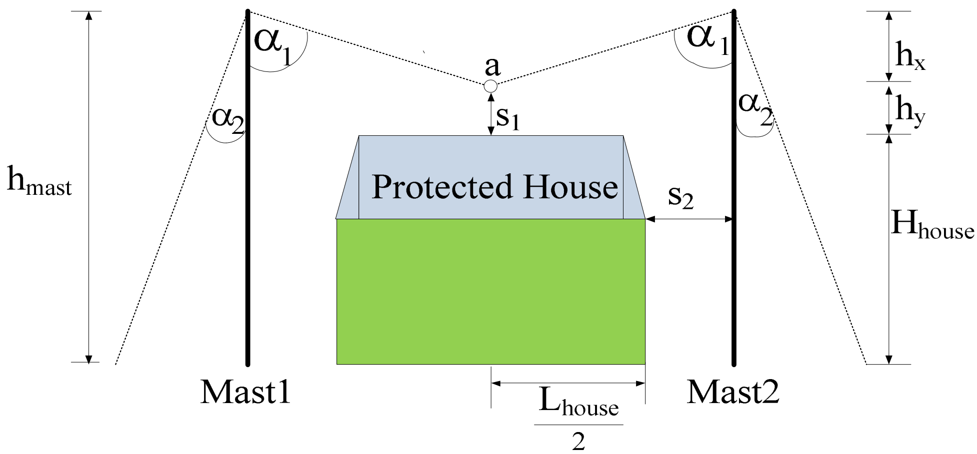

Figure 3: Criteria parameter based on protective angle of two masts

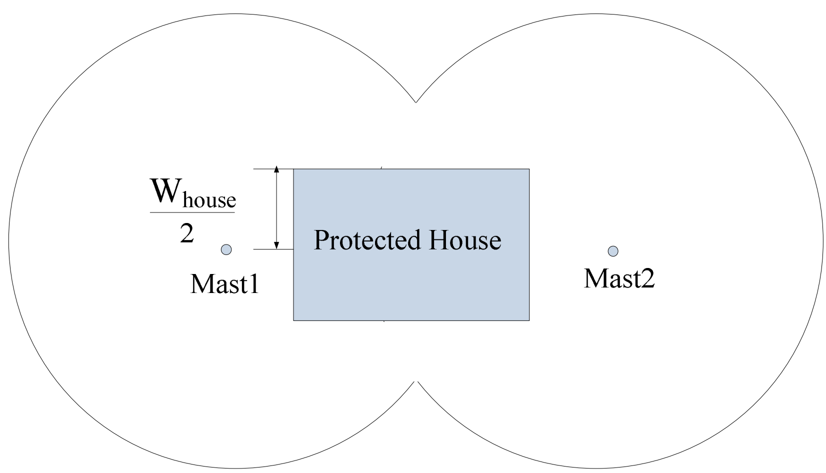

Figure 4: Top view protection zone based on protective angle,α_2

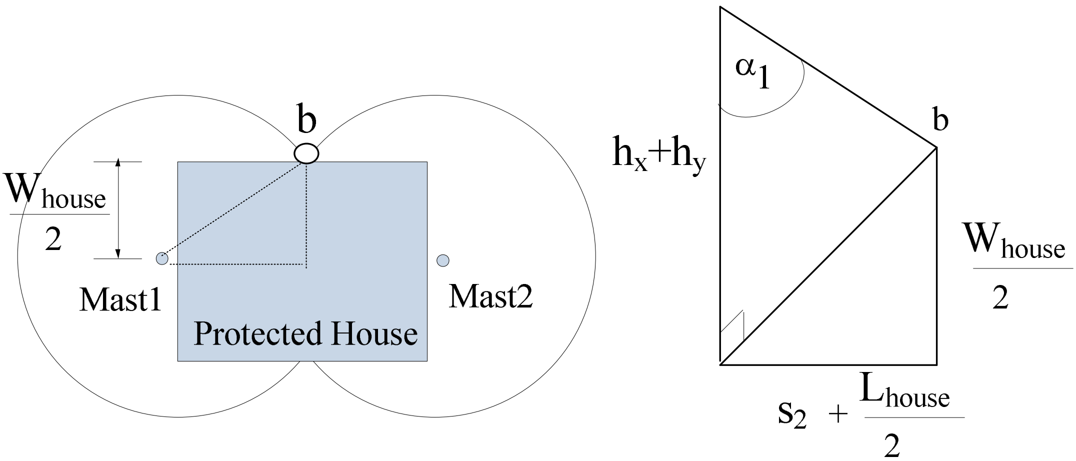

Figure 5: Top view protection zone according to protective angle, α_2

α_1 : protective angle in (1) using roof as reference of the height

α_2 : protective angle in (1) using ground as reference of the height

a : the intersection points between protective conesin Figure 3

h_x : the depth from the virtual horizontal line to point **a** (m)

h_y : safety margin between point **a** and the roof(m)

s_1 : clearance between point **a** and the roof(m)

s_2 : separation distance to avoid sparking from down conductor to the protected house (m)

H_{house} : the height of house (m)

L_{house} : the length of house (m)

W_{house} : the width of house (m)

2.3 Problem formulation

The objective of LPS design is to find the minimum of the mast height, h_{mast} while satisfying the following constraints.

a) Protective angle α_1

$$\alpha_1 = \sin^{-1}\left(1 - \frac{h_x + h_y}{\sqrt{3} \cdot R}\right) , \tag{2}$$

$$\alpha_1 = \tan^{-1}\left(\frac{\frac{1}{2} L_{house} + s_2}{h_x}\right) , \tag{3}$$

$$R_{c1} \geq \sqrt{(s_2 + \frac{L_{house}}{2})^2 + (\frac{W_{house}}{2})^2} \tag{4}$$

where R_{c1} is the radius of protective cone corresponding to α_1 at the level of h_x.

$$R_{c1} = h_x \tan(\alpha_1) \ , \tag{5}$$

b) Protective angle α_2

$$\alpha_2 = \sin^{-1}(1 - \frac{h_{mast}}{\sqrt{3} \cdot R}) \ , \tag{6}$$

$$R_{c2} \geq \sqrt{(s_2 + \frac{L_{house}}{2})^2 + (\frac{W_{house}}{2})^2} \tag{7}$$

where R_{c2} is the radius of protective cone corresponding to α_2 at the grounding level.

$$R_{c2} = h_{mast} \tan(\alpha_2) \ , \tag{8}$$

c) Separation distance s_2,

$$s_2 = \frac{k_i k_c h_{mast}}{k_m} \ , \tag{9}$$

The value of k_i according to IEC 62305 should be 0.08, and 0.06 for LPS class I and II, respectively, whereas k_i for class III and IV is 0.04. The constant k_m equals "1" for isolated external masts. The partitioning coefficient k_c of lightning current for single down conductor is set to "1" according to IEC 62305. The separation distance between a mast and the house, s_2 should not be less than 3 m for personal safety according to protection against touch and step voltages. Thus, the value of s_2 should satisfy (10). Lastly, the height of the mast must be less than rolling sphere radius, therefore, h_{mast} must satisfy (13).

$$s_2 \geq s_c \tag{10}$$

where $s_c = \max(3, \frac{k_i k_c h_{mast}}{k_m})$ (11)

$$h_{mast} = h_x + h_y + H_{house} \tag{12}$$

$$h_{mast} \leq R \tag{13}$$

3 HNM algorithms

HNM process starts after the dimension of the house, LPS class and h_y are given. The rolling sphere radius, R is defined corresponding to LPS class. After that, HNM processes iterations until h_x is converged to the final value or iteration counter exceeds the maximum value. Then, h_{mast} and protective angle, α_2, are calculated. Finally, if all constraints are satisfied, the height of masts and separation distance are recorded.

The HNM procedure is as follows.

Step 1 The dimension of the protected house, LPS class, h_y and tolerance ε, are given.

Step 2 Pick up the corresponding values of R, k_i, W_{house}, L_{house} and H_{house}.

Step 3 Set the initial value of $h_x^{(1)}$ and set iteration counter, $k = 1$

Step 4 Compute $\alpha_1^{(k)}$ from (14).

$$\alpha_1^{(k)} = \sin^{-1}(1 - \frac{h_x^{(k)} + h_y}{\sqrt{3} \cdot R}) \tag{14}$$

Step5 Compute $s_2^{(k)}$ from (15), $s_c^{(k)}$ from (16), and $h_x^{(k+1)}$ from (17) which is modified from (4) and (5).

$$s_2^{(k)} \geq s_c^{(k)} \tag{15}$$

$$s_c^{(k)} = \max(3,\ \ k_i (h_x^{(k)} + h_y + H_{house})) \tag{16}$$

$$h_x^{(k+1)} = \frac{\sqrt{(s_2 + \frac{L_{house}}{2})^2 + (\frac{W_{house}}{2})^2}}{\tan(\alpha_1)} \tag{17}$$

Step 6 If $\left| h_x^{(k+1)} - h_x^{(k)} \right| \geq \varepsilon$ and $k<k_{max}$, $k = k+1$, go to Step 4.

Step 7 Compute h_{mast} from (18).

$$h_{mast} = h_x^{(k+1)} + h_y + H_{house} \tag{18}$$

Step 8 Compute α_2 from (6).

Step 9 Compute R_{c2} from (8).

Step 10 If constraints (7) and (13) are satisfied, record the value of h_{mast}, and $s_2^{(k)}$.

Step 11 Terminate.

4 Numerical results

HNM is tested on houses with two dimensions as shown in Table 2, case A and B. In case A1 and A2, a moderate house is grounded and fulfilled with IEC 62305 conditions to reduce hazard to a tolerable level. Therefore, the separation distance between house and masts should comply with (9). The safety margin, h_y is set equal to 0 and 1 m for case A1 and A2, respectively. It could be interpreted that 1 m of h_y will keep the intersection points between two cones 1 m above the roof whereas 0 m of h_y, the roof may expose to a risk to direct strike.

In case A3 and A4, the size of the house is the same size as in case A1 and A2. But it is not attempted to provide an additional grounding system. Thus, it is a normal house without grounding system and it is not fulfilled IEC 62305 conditions, the separation distance constraint in (15) should be satisfied. The safety margin, h_y is set equal to 0 and 1 m for case A3 and A4, respectively.

For case B, it is similar to case A but the size of the protected house is bigger.

Table 2: Test cases: case A and case B

Case	W_{house}(m)	L_{house} (m)	H_{house} (m)	$s_2$constraint	h_y(m)
Case A1	6	10	10	(9)	0
Case A2	6	10	10	(9)	1
Case A3	6	10	10	(15)	0
Case A4	6	10	10	(15)	1
Case B1	12	12	20	(9)	0
Case B2	12	12	20	(9)	1
Case B3	12	12	20	(15)	0
Case B4	12	12	20	(15)	1

For case A, HNM is tested to design LPS for a moderate house. Numerical results of case A1 are shown in Table 3, lightning protection system with two masts for a moderate house with grounding system but without safety margin. The highest mast and the longest separation distance, s_2 are in LPS class I because it is the best protection class. The mast height for LPS class II, III and IV descends relatively due to the corresponding rolling sphere radius.

LPS class III is recommended in [7]. However, the protective angle, α_1 in LPS class III and IV in Table 3, is larger than the limited angle in Figure 1. Thus, the house is not protected. The house in case A2 is safer due to the safety margin, h_y= 1 m. This affects in higher mast, 12.69 m each and farther separation distance, s_2 = 0.51 m for LPS class III as shown in Table 4.

In case A2, for LPS class III, the farthest point of the house from the mast is 6.27 m calculated from square root of $(s_2 + \frac{L_{house}}{2})^2 + (\frac{W_{house}}{2})^2$. The radius of protective cone at 1 m the roof level R_{c1} is 6.27 m. But the radius of protective cone at the roof level is 9.97 m calculated from $(h_x + h_y) \cdot \tan(\alpha_1)$. The radius of the cone at the roof level is much larger than the distance to the farthest point. Thus, protective cones from two masts at the roof level cover the roof completely. The safety margin 1 m keeps the intersection point between two cones1 m high above the roof and causes larger separation distance, s_2 which consequently causes higher mast.

The protective angles α_1 and α_2 are larger as the height of mast decreases according to (1). The protective angles α_1 defines the protected volume at the roof level at the side along with the length of the house and along with the distance between two masts. The protective angles α_2 defines the protective volume at the ground level. Angle α_1 is much larger than α_2 since the height $h_x + h_y$ is much shorter than the mast height, h_{mast}. The protected house must be within protective volume defined by the protective angles α_1 and α_2.

Table 3: Case A1, grounded house with safety margin, H_y = 0

LPS class	h_{mast}(m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	13.01	3.01	65.92 °	38.63 °	1.04	6.75	10.4
II	11.68	1.68	75.40 °	50.83 °	0.70	6.44	14.33

III	**11.01**	**1.01**	**80.77 º**	**59.18 º**	**0.44**	**6.21**	**18.45**
IV	10.75	0.75	83.12 º	63.71 º	0.43	6.20	21.76

Table 4: Case A2, grounded house with safety margin, H_y = 1 m

LPS class	h_{mast}(m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	15.38	4.38	57.63 º	33.77 º	1.23	6.92	10.29
II	13.55	2.95	68.70 º	47.66 º	0.81	6.54	14.87
III	**12.69**	**1.69**	**74.90 º**	**56.84 º**	**0.51**	**6.27**	**19.43**
IV	12.36	1.36	77.78 º	61.78 º	0.49	6.26	23.02

If the protected house is ungrounded, the separation distance in (11) is 3 m for all LPS classes since the value of the term $\frac{k_i k_c h_{mast}}{k_m}$ is much less than 3m. Numerical results for case A3, lightning protection with zero safety margin, the height of the mast in LPS class III is 11.95 m with separation distance 3 m as shown in Table 5. The radius of protection cone at the roof level R_{c1} is 8.54 m which equals to the distance from a mast to the farthest point. Thus, protection cones from two masts at the roof level cover the roof. At the ground level, the radius of a protection cone R_{c2} is 19.02 m which covers the house entirely.

Adding the 1 m safety margin in case A4 will cause higher mast to be 13.75 m each, for LPS class III compared with case A3 as shown in Table 6. The location of masts is the same as in case A3. In case A4, the radius of protective cone at the roof level is 11.64 m whereas the radius of protective cone at 1 m above the roof level is 8.54 m. At the ground level, the radius of a protection cone R_{c2} is 19.97 m which covers the house entirely.

Table 5: Case A3, ungrounded house with safety margin, H_y = 0 m

LPS class	h_{mast}(m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	15.58	5.48	57.34 º	33.60 º	3	8.544	10.28
II	13.08	3.08	70.17 º	48.44 º	3	8.544	14.75
III	**11.95**	**1.95**	**77.17 º**	**57.86 º**	**3**	**8.544**	**19.02**
IV	11.44	1.44	80.47 º	62.87 º	3	8.544	22.32

Table 6: Case A4, ungrounded house with safety margin, H_y = 1 m

LPS class	h_{mast}(m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	18.30	7.30	49.52 º	28.16 º	3	8.544	9.79
II	15.09	4.09	64.44 º	45.21 º	3	8.544	15.20
III	**13.75**	**2.75**	**72.15 º**	**55.44 º**	**3**	**8.544**	**19.97**
IV	13.15	2.15	75.85 º	60.86 º	3	8.544	23.60

For a bigger house in case B, LPS class I could not be used because the designed mast is higher than the corresponding rolling sphere radius, 20 m. For LPS class III, the mast is 22.24 m each, with separation distance 0.89 m away from the house in case B1 as shown in Table 7. For a big house with 1 m safety margin in case B2, the mast is higher to be 24.11 m each, located 0.96 m from the house, for LPS class III as shown in Table 8.

Table 7: Case B1, grounded house with safety margin, $H_y = 0$ m

LPS class	h_{mast}(m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	-	-	-	-	-	-	-
II	23.96	3.96	67.48 ^{o}	32.61 ^{o}	1.44	9.56	15.33
III	**22.24**	**2.24**	**76.24 ^{o}**	**45.62 ^{o}**	**0.89**	**9.14**	**22.72**
IV	21.64	1.64	79.81 ^{o}	52.35 ^{o}	0.87	9.12	28.05

Table 8: Case B2, grounded house with safety margin, $H_y = 1$ m

LPS class	h_{mast}(m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	-	-	-	-	-	-	-
II	26.19	5.19	61.74 ^{o}	29.73 ^{o}	1.57	9.66	14.96
III	**24.11**	**3.11**	**71.31 ^{o}**	**43.68 ^{o}**	**0.96**	**9.19**	**23.03**
IV	23.41	2.41	75.28 ^{o}	50.78 ^{o}	0.94	9.17	28.18

For a big house without grounding system in case B3 causes higher mast to be 23.20 m for LPS class III, located at 3 m far away from the house without safety margin. The numerical results are shown in Table 9. When safety margin is set to be 1 m in case B4, this causes the mast become higher, 25.13 m for LPS class III and located at 3 m far away from the house as shown in Table 10.

Table 9: Case B3, ungrounded house with safety margin, $H_y = 0$ m

LPS class	h_{mast}(m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	-	-	-	-	-	-	-
II	25.30	5.30	63.90 ^{o}	30.87 ^{o}	3	10.82	15.12
III	**23.20**	**3.20**	**73.53 ^{o}**	**44.62 ^{o}**	**3**	**10.82**	**22.89**
IV	22.33	2.33	77.85 ^{o}	51.73 ^{o}	3	10.82	28.31

Table 10: Case B4, ungrounded house with safety margin, $H_y = 1$ m

LPS class	h_{mast}m)	h_x(m)	α_1	α_2	s_2(m)	R_{c1}(m)	R_{c2}(m)
I	-	-	-	-	-	-	-
II	27.60	6.60	58.63 ^{o}	27.97 ^{o}	3	10.82	14.65
III	**25.13**	**4.13**	**69.09 ^{o}**	**42.65 ^{o}**	**3**	**10.82**	**23.15**
IV	24.15	3.15	73.75 ^{o}	50.14 ^{o}	3	10.82	28.92

Mast in LPS class I for cases A1 – A4, is the highest one since it is the best protection. However, it is the most expensive. Lightning protection with two masts using LPS class I could not be employed to protect a big house in case B, protection with four masts should be used instead. Home owner should make decision to select the LPS class since better LPS class will result in higher mast and higher cost. Trade-off based on economics should be considered to compare the damage and repair cost with the protection cost.

5 Discussions

According to IEC 62305, in certain conditions, it is possible to cause injuries of living beings in the vicinity of mast being a down conductor. It may be hazardous to life. Protection measures against touch voltages could be either insulating the mast or imposing physical restrictions and warning notice to prevent persons from touching mast. Whereas, protection measures against step voltages could be equipotentialising with a mesh earth-termination system or physical restrictions and warning notice to prevent persons from approaching to dangerous area within 3 m of masts. However, the hazard could be reduced to a tolerable level if the resistivity of the surface within 3 m is not less than 5 kΩm or insulating material, e.g. asphalt is used. Thus, if one of the above protection measures is fulfilled, the separation distance, s_2, could be less than 3 m. This causes shorter mast compared with 3 m separation distance as shown in numerical results. However, shorter distance s_2 may be inconvenient because masts are too close to the protected house. Thus a designer should consider the scenery and the convenience of home owners.

In addition, the safety margin should be considered. Zero margin may expose to a risk due to land surface transformation, mast oscillation during storm, etc. If the intersection point of the protective cone, point a is lower than the roof, there will be an unprotected area. The appropriate safety margin should be further studied. However, the larger margin will cause higher mast and higher cost. Thus, the cost of masts and protection measures, LPS class selection, safety margin, available space and surroundings should be considered carefully.

6 Conclusions

Isolated external air terminal masts are used to protect roof-mounted solar cell. In this paper, the height and the location of masts according to IEC standard 62305 are designed by applying heuristic numerical method, HNM. The numerical results indicate that the proposed method, HNM could be used effectively and accurately. It will be convenient for engineers to use HNM to design an isolated external air terminal mast for a protected house.

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