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Analysis of necessary separation distances for lightning protection systems including natural components

Fridolin Heidler and Wolfgang Zischank, *University of the Federal Armed Forces Munich, Neubiberg*
Alexander Kern, *University of Applied Sciences, Aachen*

***Abstract*— In case of a direct lightning strike to a building dangerous sparking may occur between the external lightning protection system and conductive installations inside the building. To avoid such side flashes a minimum separation distance between conductive parts inside the building and the air termination or down conductor system is required. The standard IEC 62305-3 [7] provides a formula to determine the necessary separation distance. The formula originally was developed in the early 1980s for simple structures. Nowadays significantly improved computer codes are available. Objective of the paper is to re-visit the determination of separation distances. Secondly, the necessary separation distance for buildings using a metal roof as natural component of the air termination system is investigated. Such configurations are not covered yet by the IEC-formula.**

***Index Terms*-- IEC 62305-3 standard, lightning, lightning protection, metallic roof, method of moments, return stroke, separation distance.**

I. Introduction

According to the standard IEC 62305-3 [7] the necessary separation distance between the air termination system or down conductors and conductive installations inside a building is determined by the following equation:

$$s > k_i \cdot \frac{k_c}{k_m} \cdot \ell \qquad (1)$$

The coefficient k_i contains the current steepness of the subsequent stroke, the mutual inductance between down conductor and the induction loop as well as the dielectric strength of air for sub-microsecond impulse voltages [12]. The coefficient k_c takes into account the current share to the individual down conductors. The coefficient k_m finally considers the dielectric strength of materials other than air present at the location of the proximity. For air $k_m = 1$.

Equ. 1 and the values for the parameters are based on calculations published by *Steinbigler* in the mid 1980s [11]. Due to the limited computer capacity available at that time, the modeling was limited to simple one-, two-, and three dimensional (cubic) lightning protection systems consisting of only stretched wires.

Originally, the formula was developed using the ***vertical*** distance between the point, where the separation distance is to be considered, to the nearest equipotential bonding point for the length l. Meanwhile the length has been re-defined in the IEC 62305-3 standard as the ***total*** length ***along*** the air termination and the down conductors from the point, where the separation distance is to be considered to the nearest equipotential bonding point. The formula for k_c later on was refined taking into account the height of the structure and the distance between the down conductors. In the latest edition of the IEC lightning standard [7] the values for k_i have been reduced by 20 %.

Objective of the paper is to test the IEC equation for separation distances with state of the art computer codes solving the complete Maxwell equations. Further, more complex structures including metal roofs are investigated in order to determine the reduction of induced voltages by such plane metal structures. Such structures, where the metal roof is used as "natural components", are not yet covered by the present method of IEC 62305-3 [7].

II. Computational Approach

The electromagnetic computations are carried using the computer code "CONCEPT", which has been developed during the last two decades by the Technical Uni-

Contact Address:
Fridolin HEIDLER
University of the Federal Armed Forces Munich
Department of Electrical Engineering, EIT 7
Werner-Heisenberg-Weg 39, D – 85577 Neubiberg, Germany.
E-mail: Fridolin.Heidler@unibw.de

versity Hamburg-Harburg [2]. This computer code is based on the so-called Method of Moments (MOM) [3] and is written in FORTRAN 77. It is a well-known computer code in the area of electromagnetic computations, and has been validated by several tests [2, 10]. This computer code solves the complete Maxwell's equations in the frequency domain. Therefore, the time-domain solutions of currents and voltages are obtained from the inverse Fourier transformation. The fundamental assumptions of the computer code are given in [2] and the handling of the program package is described in [8].

A. Simulation of the return stroke process

In the computer code CONCEPT, the return stroke process can be simulated with the transmission-line (TL) - model introduced by *Uman* [1]. Using this model, the return stroke channel is assumed to be straight and perpendicular to the earth surface. The return stroke channel is considered to increase along the z-coordinate with the constant return stroke velocity chosen to v = 100 m/µs.

The TL – model uses a pre-defined current source $i_B(t)$ at the channel-base, from where the time-varying current waveform propagates upwards in z-direction. This behavior is transferred to the frequency domain using the time shifting theorem of the Fourier analysis. From that results a current source at the attachment point, where the phase velocity is given by the return stroke velocity v [9].

The separation distance is determined from the magnetically induced voltages of subsequent return strokes. According to the IEC 62305-1 standard [6], the channel-base current $i_B(t)$ of subsequent stroke is simulated with a front time of T_1 = 250 ns. The following channel-base current it considered in the paper:

$$i_B(t) = \begin{cases} \dfrac{i_{B/\max}}{T_1} t, & \text{for } 0 \le t \le T_1 \\ i_{B/\max}, & \text{for } t \ge T_1 \end{cases} \qquad (2)$$

Equ. 2 defines a lightning current with a constant steepness during the current rise. After the current rise the current is kept constant at the peak value $i_{B/max}$.

B. Modelling of the electrical structure

The so-called thin wire approach is used to simulate the cylindrical conductors. The cylindrical conductors of the air termination system and of the down conductor system are taken into account with the radius of 4 mm and with the conductivity of $56{,}2 \cdot 10^6$ S/m. These values are typical for an external lightning protection system consisting of copper. The flat metal roofs are simulated by rectangular and triangular patches assumed as ideal conductors. The ground is considered as plane also with ideal conductivity.

Three different frequency regimes are chosen in order to minimize the number of frequencies. Starting with a lowest frequency of 1 kHz, the frequency is increased in steps of Δf = 2 kHz up to 99 kHz. Then in the second frequency regime, the frequency step is increased to Δf = 3 kHz up to 2 MHz. In the highest frequency regime between 2 MHz and 20 MHz, the frequency step is further increased to Δf = 4 kHz.

As a general rule, the dimensions of the wires and of the patches should not exceed about $\lambda/8$, where λ is the wavelength of the highest frequency considered. In the paper, the highest considered frequency of 20 MHz corresponds to the wavelength of 15 m. Consequently, the wires and patches were subdivided into segments with maximum dimensions of 2 m.

III. EXAMINED STRUCTURES

The following three structures are selected for the study (fig. 1 and fig. 2):

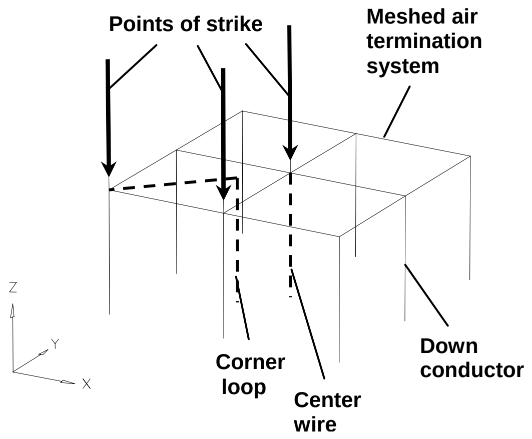
- Structure 1 simulates a building with a base of 20 m x 20 m and a height of 10 m.
- Structure 2 is a building with the same 20 m x 20 m base, having a height of 20 m.
- Structure 3 represents an industrial plant with a 60 m x 60 m base having a height of 10 m.

The structures are protected by two different kinds of air termination systems. In the first case shown in fig. 1, the air termination system consists of meshed air termination wires. In the second case the structures are covered by flat metal roofs used as "natural component" air termination system (fig. 2).

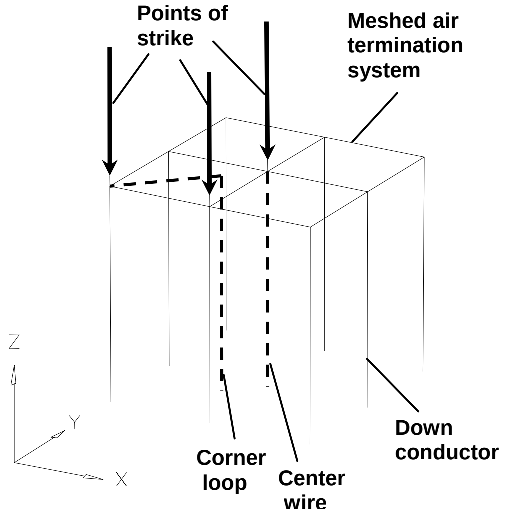
The lightning protection is designed according to class II of IEC 62305-3 [7]: The mesh size of the air termination system is 10 m x 10 m and the interspacing between the down conductors is 10 m.

Three different lightning attachment points have been considered, to the corner of the roof, to the middle of the roof side and to the center of the roof. For calculation purposes, at these locations short lightning rods of 1 m length are placed and connected to the air termination system. The channel-base current is injected to the top of these rods. According to LPL II the peak value of a subsequent stroke is $i_{B/max}$ = 37,5 kA, the front time being T_1 = 250 ns.

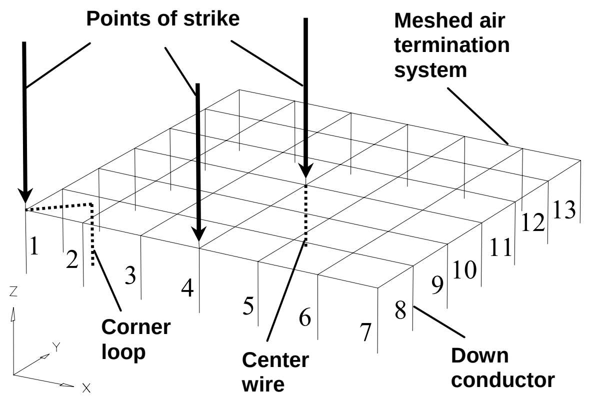
For the evaluation of the separation distance two wire routings are installed inside each structure. They are denoted as corner loop and center wire and shown as dashed lines in fig. 1 and fig. 2. Each wire is loaded by a high resistance of 1 MΩ in order to simulate the open loop conditions at proximity between the lightning protection system and internal conductive parts. The corner loop starts from the corner of the air termination system with a 10 m long horizontal section pointing diagonally to the center of the structure. Following a vertical section goes down to ground. Of course, in case of the flat metal roof the horizontal section is missing. Further, in this case the vertical section is slightly inclined due to the segmentation rules of the CONCEPT computer code. The center wire connects the air termination system and the ground in the middle of the structure.



a) Structure dimensions: Length 20 m, width 20 m, height 10m

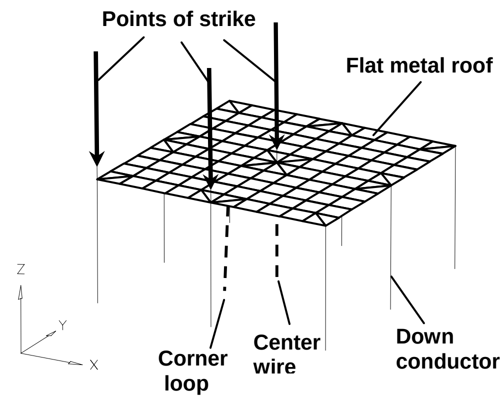


b) Structure dimensions: Length 20 m, width 20 m, height 20m

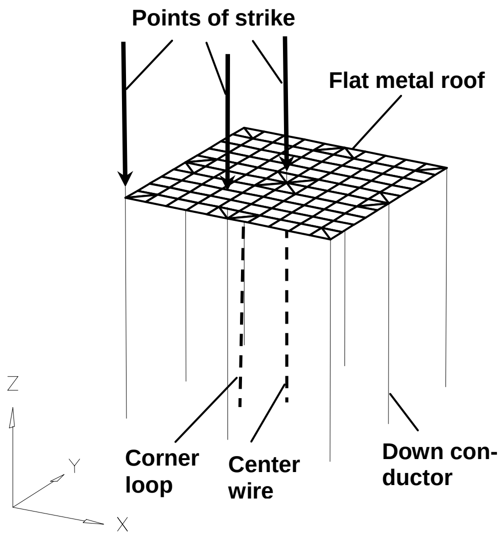


c) Structure dimensions: Length 60 m, width 60 m, height 10 m

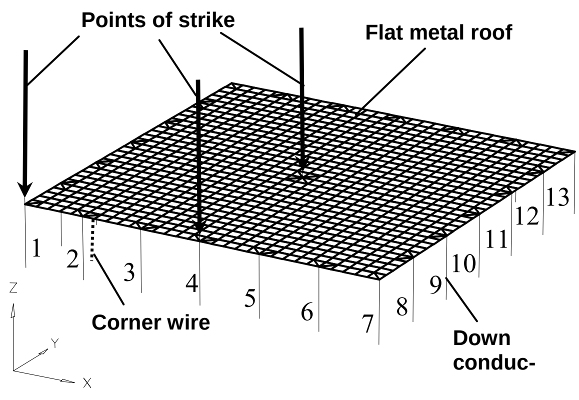
Fig. 1. Structures with meshed air termination system of 10 m x 10 m mesh size and down conductors with 10 m interspacing.



a) Structure dimensions: Length 20 m, width 20 m, height 10m



b) Structure dimensions: Length 20 m, width 20 m, height 20m



c) Structure dimensions: Length 60 m, width 60 m, height 10m

Fig. 2. Structures with flat metal roof and down conductors with 10 m interspacing.

IV. Results

A. Current distribution to the down conductors

The share of the injected current to the down conductors is determined for the asymmetric case of a lightning strike to the corner of the roof. Of special interest is the current through the corner down conductor located directly beneath the point of strike: The ratio of the peak current through this down conductor, $i_{1/max}$, to the peak of the incident lightning current, $i_{B/max}$, equals to the parameter k_c of equ. 1. Table I gives the ratios of the corner down conductor peak current $i_{1/max}$ to the incident lightning current peak $i_B/_{max}$ for the meshed air termination system and the flat metal roof. In comparison to the meshed wire air termination also the values of k_c according to IEC 62305-3 [7] are listed in table I.

TABLE I
RATIO OF THE CORNER DOWN CONDUCTOR CURRENT TO THE INCIDENT LIGHTNING CURRENT FOR STRIKES TO THE CORNER

Structure size	$i_{1/max}$ / $i_{B/max}$		
	meshed wire	k_c acc. to IEC 62305-3	flat metal roof
20m x 20m x 10m	0,40	0,36	0,25
20m x 20m x 20m	0,33	0,32	0,22
60m x 60m x 10m	0,39	0,32	0,22

In case of the structures with meshed air termination systems the values for k_c according to IEC are in good agreement to the values calculated, the maximum deviation being 18 % in case of the large 60 m x 60 m structure. Fig. 3 shows the percentage current share p = $i_{n/max}$ / $i_{B/max}$ to the down conductors for the large 60 m x 60 m base structure. The numbering "n" of the down conductors can be seen from fig. 1 and 2. Obviously, the down conductor at the corner and its immediate neighbours carry the bulk of the current, while the rest of the down conductor diverts only 5 % or less of the incident lightning current to ground. It should be noted that also in the case of the metal roof a remarkable part of the incident current flows through the corner down conductor (about 22 %), although it is clearly less compared to the case of a meshed wire air termination (about 40 %).

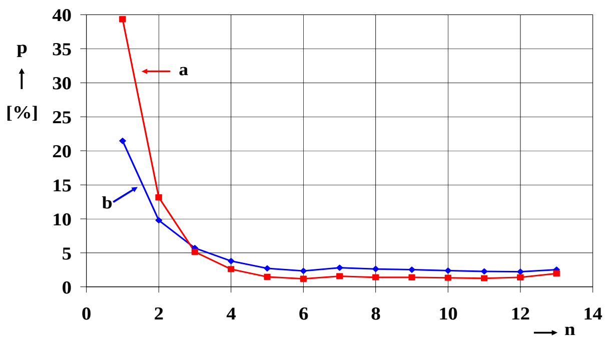
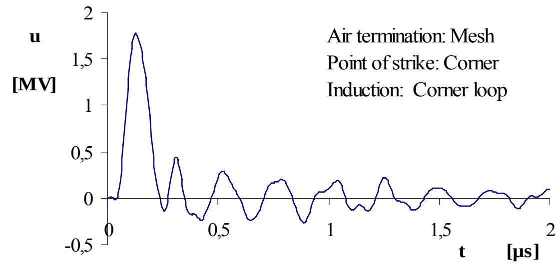


Fig. 3. Percentage current distribution to the down conductors for the 60 m x 60 m x 10 m structure, lightning strike to the roof corner
a) Meshed air termination b) Flat metal roof

B. Induced voltages

The fig. 4 gives two examples of the induced voltage waveshapes: Almost any waveshape may occur, from a dominant peak at the beginning followed by only minor oscillations up to only slightly damped oscillations.



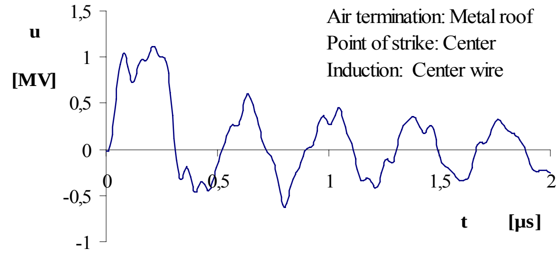


Fig. 4. Examples of induced voltage waveshapes

The peak values of the induced voltages are listed in the tables II and III. In case of meshed wire air termination systems the highest voltage is always induced to the corner loop, when lightning strikes the corner of the roof. But also the voltage induced to the center wire is remarkable high in case of a strike to the roof center. For these two worst cases the induced voltage does not increase linear with the structure height. Doubling the structure height results only in an increase of the induced voltage by a factor of roughly 1,4. Comparing the two 10 m high structures shows that the worst case voltages are fairly independent of the base dimensions.

In case of the flat metal roof structures with a 20 m x 20 m base the induced voltages are pretty much the same, independent on the point of strike and the induction loop location. Only the large 60 m x 60 m base structure shows higher induction in case of the corner strike. The induced voltage increases almost linear with the height of the structure: Increasing the structure height from 10 m to 20 m the increases voltage by about a factor of 1,9.

TABLE II
PEAK VOLTAGES FOR MESHED WIRE AIR TERMINATION

Structure size	Induction to	Peak voltage [kV]		
		Point of strike		
		Corner	Side	Center
20 m x 20 m 10 m high	corner loop	1770	628	506
	center wire	471	426	1030
20 m x 20 m 20 m high	corner loop	2490	1140	1140
	center wire	737	657	1390
60 m x 60 m 10 m high	corner loop	1780	155	243
	center wire	257	247	1120

TABLE III
PEAK VOLTAGES FOR FLAT METAL ROOF

Structure size	Induction to	Peak voltage [kV]		
		Point of strike		
		Corner	Side	Center
20 m x 20 m 10 m high	corner loop	336	327	325
	center wire	321	321	317
20 m x 20 m 20 m high	corner loop	633	618	595
	center wire	593	598	608
60 m x 60 m 10 m high	corner loop	256	101	84,5
	center wire	147	109	117

C. Influence of the lightning current waveform

For comparison, calculations were also performed using lightning current waveforms other than the linear rise according to equ. 2. In these cases, the injected negative subsequent stroke ($i_{B/max}$ = 37,5 kA, T_1 = 250 ns) was simulated using the standardized lightning waveform of IEC 62305-1 [6] (equ. 3) as well as a double exponential current waveform (equ. 4).

$$i_B(t) = \frac{i_{B/\max}}{\eta} \cdot \frac{(t/T)^{10}}{1+(t/T)^{10}} \cdot e^{-t/\tau} \quad (3)$$

$$i_B(t) = \frac{i_{B/\max}}{\eta} \cdot \left(e^{-t/\tau_1} - e^{-t/\tau_2}\right) \quad (4)$$

The comparison was performed for the 20 m x 20 m x 10 m structure and with lightning current injection to the roof corner. The maximum voltages induced to the corner loop are quite similar for the linear rising current waveform (equ. 2) and the IEC current given in equ. 3. Differences here are less than 25 %. Compared to the linear rising current waveform, the double exponential current waveform (equ. 4), however, produces maximum voltages about twice as high. This is due to the significantly higher maximum current steepness inherent to a double exponential current waveform.

V. SEPARATION DISTANCES

The necessary separation distance depends on the amplitude and waveshape of the induced voltage and on the dielectric strength. The dielectric strength again is a function of the voltage waveshape. For the determination of the necessary separation distance s the well established constant-area-criterion [4] is used. For unipolar impulse voltages of arbitrary waveshape the following equ. 5 must be fulfilled:

$$\int_{t_1}^{t_2} [u(t) - U_0] \cdot dt = A \quad (5)$$

The definitions used in equ. 5 are illustrated in fig. 5. Both the parameters A and U_0 are functions of the separation distance s. For rod-rod gaps exposed to negative impulse voltages the following values can be applied [5]:

$U_0 = 0{,}63 \cdot s$ (MV) and $A = 0{,}59 \cdot s$ (V·s)

with the separation distance s in meter.

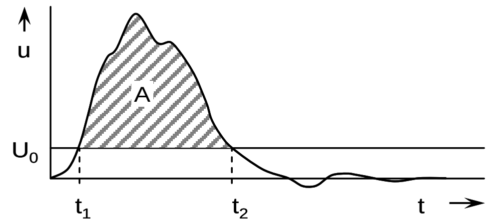


Fig. 5. Illustration of the constant-area-criterion

The tables IV and V contain the separation distance for the various structures, points of strike and induction loops. The general tendencies observed for the induced voltages (see section IV.B) are also valid for the separation distances. These worst cases are marked in table IV by the shaded areas.

TABLE IV
SEPARATION DISTANCE FOR MESHED WIRE AIR TERMINATION

Structure size	Induction to	Separation distance [cm]		
		Point of strike		
		Corner	Side	Center
20 m x 20 m 10 m high	corner loop	29	9,6	7,3
	center wire	6,1	9,0	23
20 m x 20 m 20 m high	corner loop	46	23	19
	center wire	17	19	34
60 m x 60 m 10 m high	corner loop	28	2,1	3,2
	center wire	2,5	3,7	32

TABLE V
SEPARATION DISTANCE FOR FLAT METAL ROOF

Structure size	Induction to	Separation distance [cm]		
		Point of strike		
		Corner	Side	Center
20 m x 20 m 10 m high	corner loop	8,4	8,1	7,8
	center wire	7,6	7,8	7,8
20 m x 20 m 20 m high	corner loop	18	17	17
	center wire	17	17	17
60 m x 60 m 10 m high	corner loop	6,1	2,8	2,2
	center wire	2,4	2,6	2,6

For structures with the metal roof the separation distance is fairly independent of the point of strike and the location of the induction loop. Only for the 60 x 60 m base structure the separation distance for the corner loop in case of the corner strike differs from the other values determined for this structure. However this value (6,1 cm) is less than the value determined for the 20 m x 20 m structure of the same height. It seems that the separation distance might be determined as constant k multiplied by the structure height h:

$$s = k \cdot h \quad (6)$$

Comparing the worst case values of a meshed wire air termination (shaded areas in table IV) to the corresponding values of a metal roof demonstrates the benefits of using the metal roof as natural component: The separation distances can be reduced by a factor of 2,5 to 4,5.

VI. CALCULATIONS ACC. TO IEC 62305-3

Following a comparison to the separation distances determined according to IEC 62305-3 [7] is given for meshed wire air termination systems. For a class II LPS k_i, = 0.06 and k_m = 1 for air applies. The coefficient k_c depends only on the down-conductor system:

$$k_c = \frac{1}{2 \cdot n} + 0{,}1 + 0{,}2 \cdot \sqrt[3]{\frac{c}{h}} \qquad (7)$$

with: n total number of down-conductors
c spacing between down-conductors
h height of structure.

The length ℓ in equ. 1 is defined as the length along the air termination or/and the down-conductor from the point, where the separation distance is to be considered, to the nearest equipotential bonding point (here: ground level). For the three arrangements of fig. 1 the following lengths ℓ have to be taken:

- For the corner loop only the vertical length along a down-conductor has to be taken for the length ℓ. Therefore all three points of strike lead to the same result.
- For the center wire in case of strikes to the roof center, however, the horizontal length of the air termination wires has to be added.

Table VI gives the results of this calculation. Following the definitions and rules of IEC 62305-3, for some cases (e.g. corner loop and corner strike) the results are slightly underestimated compared to the computer analysis with CONCEPT. For some other cases (e.g. center wire and center strike) the separation distance is overdone by the IEC 62305-3 approach.

TABLE VI
SEPARATION DISTANCE FOR MESHED WIRE AIR TERMINATION ACC. TO IEC 62305-3

Structure size	Induction to	Point of strike	k_c	ℓ (m)	s (cm)
20m x 20m 10 m high	corner loop	all	0,362	10	21,7
	center wire	corner, side	0,362	10	21,7
		center	0,362	20	43,4
20m x 20m 20 m high	corner loop	all	0,321	20	38,5
	center wire	corner, side	0,321	20	38,5
		center	0,321	30	57,8
60m x 60m 10 m high	corner loop	all	0,321	10	19,3
	center wire	corner, side	0,321	10	19,3
		center	0,321	40	77,0

VII. CONCLUSION

Separation distances necessary to prevent dangerous sparking are analyzed for several structures with classical meshed wire air termination systems and with flat metal roofs used as natural component of the LPS. The induced voltages are determined using the computer code "CONCEPT". From these voltages the required separation distances are derived on the basis of the constant-area -criterion.

For meshed wire air termination systems the current share to the corner down conductor is in reasonable agreement to the k_c value of IEC 62305-3. Some differences are found for the separation distances, especially for the center wire in case of a center strike.

Using a metal roof as a natural component significantly reduces the separation distances. The separation distances are fairly independent of the point of strike and the location of the induction loop. The separation distance is predominantly a function of the structure's height.

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