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Application of Lightning Location System Data for Designing the External Lightning Protection System

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SUMMARY

This paper deals with designing and positioning of air-termination system and analyzes the effectiveness of external lightning protection system (LPS). The electro-geometric model based on rolling sphere method was used to determine the optimal height and number of air-termination installations in the oil refinery according to standard IEC 62305. The lightning parameters are essential input variables for estimating the effectiveness of external LPS. Lightning parameters derived from lightning location system (LLS) observations were compared to ones used in IEC standard. For this purpose an algorithm for assessment of the lightning flash multiplicity was developed in order to determine the current amplitude probability distribution of the first cloud to ground negative strokes. Analysis of LLS data show there is higher probability of low amplitude cloud to ground strokes occurrence compared to IEC standard. Consequently, for a given lightning protection level (LPL), the risk of the lightning terminating at the object to be protected is higher.

KEYWORDS

Lightning protection system, air-termination system, electro-geometric model, lightning location system, lightning parameters

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1. INTRODUCTION

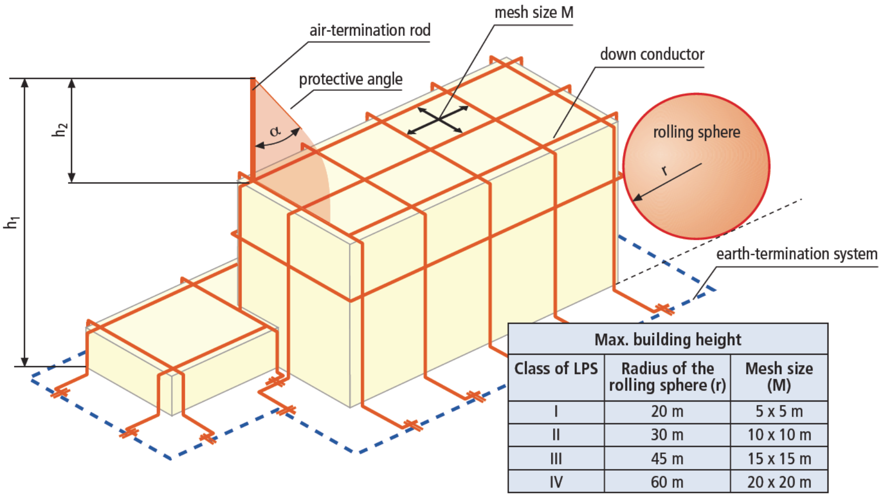
The interception effectiveness of the air-termination system is in correlation with the LPL, i.e. with the percentage of the prospective lightning strikes which are safely controlled by the air-termination system. Numerous studies showed that the final striking distance (radius of the rolling sphere) depends directly on the amplitude of lightning current. Therefore, the lightning parameters are essential input variables for estimating the effectiveness of external LPS.

The lightning current parameters used in IEC 62305-1 [1] are based on the results of Berger et al. which are derived from current waveforms measured using resistive shunts installed at the tops of two 70-m high towers [2],[3]. These results are still used to a large extent as the primary reference source for both lightning protection and lightning research.

This paper deals with designing and positioning of air-termination system in the oil refinery and analyzes the effectiveness of its external LPS. In the first part of the paper, the electro-geometric model based on rolling sphere method was used to determine the optimal height and number of air-termination installations according to [1]. The second part of the paper deals with lightning parameters obtained from LLS data for designing the external LPS.

2. AIR-TERMINATION SYSTEM

External LPS consists of an air-termination system, a down-conductor system and an earth-termination system. The function of the air-termination system as a part of external LPS is to prevent direct lightning strikes from damaging the object to be protected. By correct dimensioning of the air-termination system, the effects of a lightning strike to a structure can be reduced in a controlled way. Air-termination systems can consist of the following components: rods, spanned wires and cables and intermeshed conductors. When determining the locations of the air-termination system special attention must be paid to the protection of corners and edges of the structure to be protected. Three methods can be used to determine the arrangement and the positioning of the air-termination systems: rolling sphere method, mesh method and protective angle method (Fig. 1) [4].



Max. building height

Class of LPS	Radius of the rolling sphere (r)	Mesh size (M)
I	20 m	5 x 5 m
II	30 m	10 x 10 m
III	45 m	15 x 15 m
IV	60 m	20 x 20 m

Figure 1 Method for designing of air-termination systems for high buildings

The rolling sphere method is the universal method of design particularly recommended for geometrically complicated applications.

3. ELECTRO-GEOMETRIC MODEL

For lightning flashes to earth, a downward leader grows step-by-step from the cloud towards the earth. When the leader gets close to the earth within a few tens, to a few hundreds of metres, the electrical insulating strength of the air near the ground is exceeded. A further “leader” discharge similar to the downward leader begins to grow towards the head of the downward leader: the upward leader. This defines the point of strike of the lightning strike (Fig. 2).

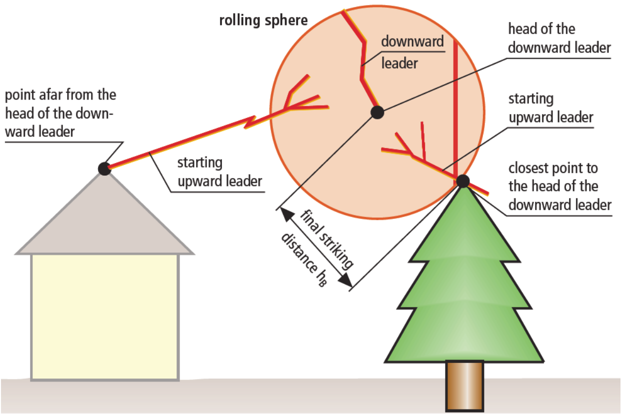


Figure 1 Starting upward leader defining the point of strike

The starting point of the upward leader and hence the subsequent point of strike is determined mainly by the head of the downward leader. The head of the downward leader can only approach the earth within a certain distance. This distance is defined by the continuously increasing electrical field strength of the ground as the head of the downward leader approaches. The smallest distance between the head of the downward leader and the starting point of the upward leader is called the final striking distance h_B which corresponds to the radius of r the rolling sphere. Immediately after the electrical insulating strength is exceeded at one point, the upward leader, which leads to the final strike and manages to cross the final striking distance, is formed. The electro-geometric model is based on the hypothesis that the head of the downward leader approaches the objects on the ground, unaffected by anything, until it reaches the final striking distance. The point of strike is then determined by the object closest to the head of the downward leader. The upward leader starting from this point develops until it reaches head of downward leader.

The protection of structures against lightning is described in standard IEC 62305-3 [5]. This standard also defines the classification of the individual LPS and stipulates the resulting lightning protection measures. It differentiates between four LPLs. LPL I provides the most protection and a LPL IV, by comparison, the least. The interception effectiveness of the air-termination systems is concomitant with the LPL of LPS, i.e. which percentage of the prospective lightning strikes is safely controlled by the air-termination systems. The minimum values of the rolling sphere radius r define the interception efficiency of the LPS according to [5]. The correlations between LPL of LPS, interception effectiveness of the air-termination systems, radius of the “rolling sphere” and current peak values are shown in Table 1. The probability p denotes the percentage of lightning with a current peak higher than the minimum values shown in Table I.

Table 1 Relations between LPL, interception effectiveness, radius of the "rolling sphere" and minimum peak value of lightning current I

Lightning protection level LPL	Probability p that peak values of current is greater than the minimum values	Minimum peak value of current I (kA)	Radius of the rolling sphere r (m)
I	99 %	3	20
II	97 %	5	30
III	91 %	10	45
IV	84 %	16	60

The centre of the "rolling sphere" used corresponds to the head of the downward leader towards which the respective upward leaders will approach. The rolling sphere is now rolled around the object under examination and the contact points representing potential points of strike are marked in each case. The rolling sphere is then rolled over the object in all directions. All potential points of strike are thus shown on the model; it is also possible to determine the areas which can be hit by lateral strikes. The naturally protected zones resulting from the geometry of the object to be protected and its surroundings can also be clearly seen. Air-termination conductors are not required at these points (Fig. 3).

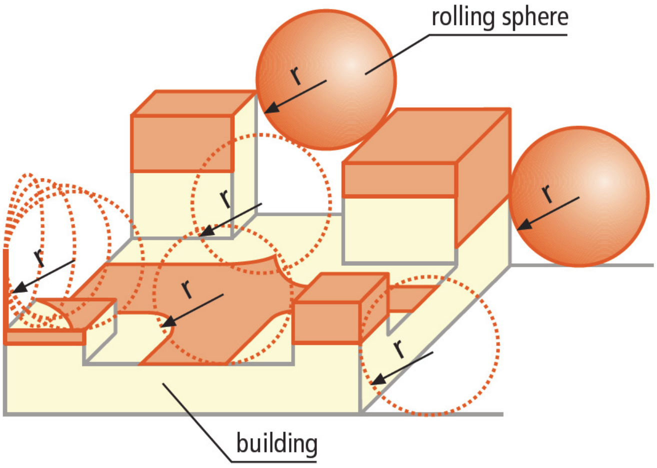


Figure 3 Rolling sphere method at a building with considerably structured surface

The electro-geometric model is used to determine height and number of air-termination installations. The sag of the rolling sphere is decisive for the dimensioning of the air-termination system, which is determined according to [5]. Numerous studies showed that the final striking distance depends directly on the amplitude of lightning current, and can be determined from the expression:

$$r = 10 \cdot I^{0.65} \tag{1}$$

r in m, I in kA.

Since the movement of lightning is stochastic, the path of the downward leader head sets in a random manner. The next point of the path of the downward leader head is any point on the hemisphere of radius r around the previous point of the trajectory (Fig. 4).

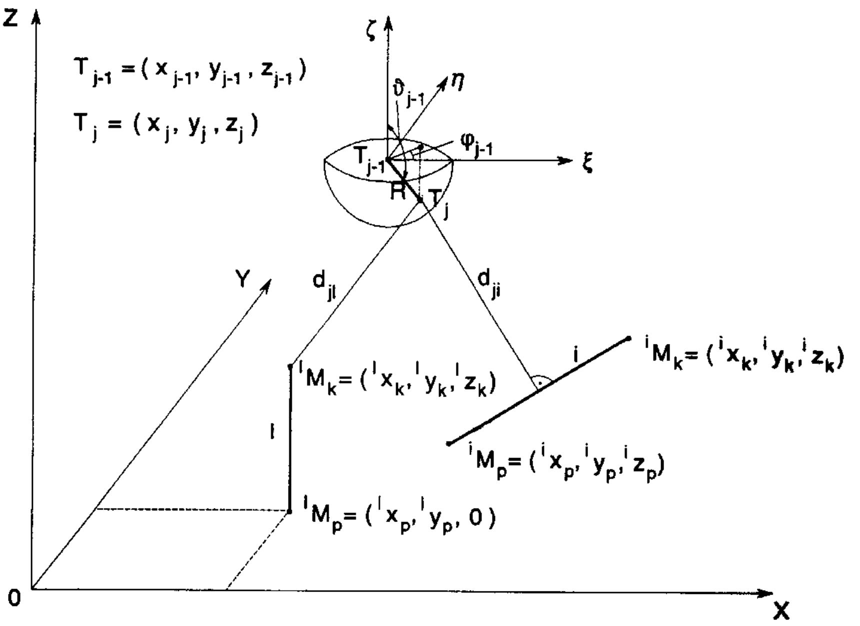


Figure 4 Determination of the distance between the head of the downward leader and objects on the ground (air-termination system, protected objects and earth surface)

Coordinates of the downward leader head are determined by the following expressions:

$$x_i = x_{i-1} + r \cdot sin\vartheta_{i-1} \cdot cos\varphi_{i-1}, \tag{2}$$

$$y_i = y_{i-1} + r \cdot sin\vartheta_{i-1} \cdot sin\varphi_{i-1}, \tag{3}$$

$$z_i = z_{i-1} + r \cdot cos\vartheta_{i-1}, \tag{4}$$

$$\varphi_{i-1} = \lambda_1 \cdot 2\pi, \tag{5}$$

$$\vartheta_{i-1} = (\lambda_2 + 1) \cdot \frac{\pi}{2}, \tag{6}$$

where: λ_1 and λ_2 are random numbers from the interval [0,1]. The expressions (2)-(6) are in a spherical coordinate system. The described mechanism is applied for the simulation of the downward leader propagation from the cloud towards the earth. Total number of elements N_e which may be exposed to direct lightning strike is given by (7).

$$N_e = N_{ats} + N_{pe} \tag{7}$$

N_{ats} – number of air-termination system elements,
N_{pe} – number of protected object elements.

Fig. 4 shows horizontal element "*i*" (protected object), the vertical element "*l*" (air-termination rod) and the position of the downward leader head in space after "*j*" steps. For example, for the *i*-th element, the coordinates of its end points are as follows: ^iM_p (^ix_p, ^iy_p, ^iz_p) and ^iM_k (^ix_k, ^iy_k, ^iz_k). Determination of the shortest distance between the head of the downward leader in the above position (point T_j) and the elements "*l*" and "*i*" requires the use of analytic geometry in space. The program for electro-geometric modelling was developed in Matlab software.

4. DESIGNING EXTERNAL LIGHTNING PROTECTION SYSTEM OF THE OIL RAFINERY

The goal of the analysis is to design and determine the positioning of air-termination system for oil refinery (Fig. 5) and analyze the effectiveness of its external LPS.

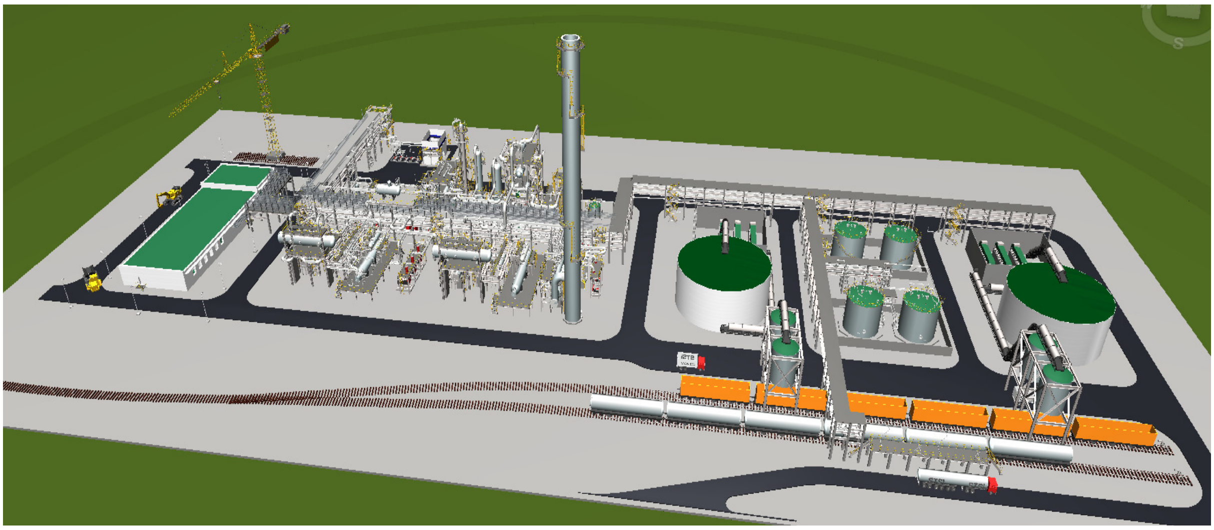


Figure 5 Oil refinery

The area of oil refinery was separated into 29 objects that should be protected from direct lightning strikes (Fig. 6).

Figure 6 Overview of 29 protected zones and objects of the oil rafinery

The corresponding LPL II for oil refinery with explosive areas requires a rolling sphere radius of r=30 m (for minimum peak value of current I=5 kA). Lightning poles as a natural components of air-termination system surrounding the oil refinery were taken into account in simulations since they also attract direct lightning strikes. In the first step, positioning and designing of the air-termination system is performed according to [5]. A large number of simulations are conducted in order to determine the optimal length and positioning of air-termination rods and mesh conductors. Figs 7 and 8 show a case when 10000 lightning strikes were simulated of which 8729 hit ground, 1268 air-termination system (blue colour) and 3 protected objects 21 and 22 (red colour) which are explosive areas (fuel tanks).

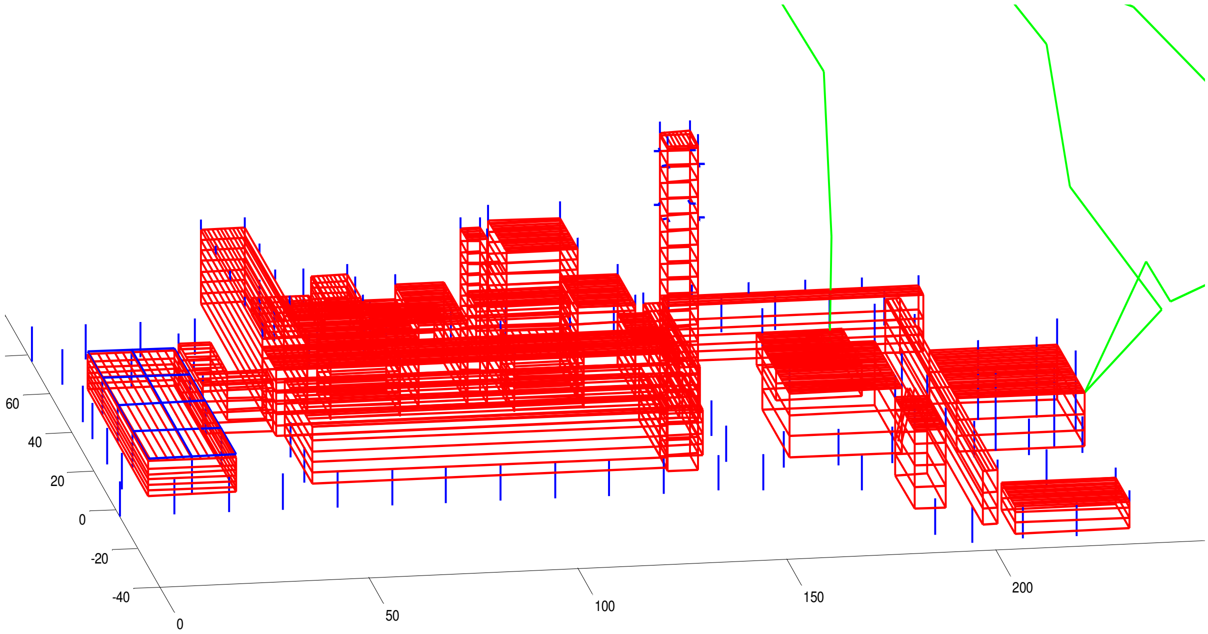


Figure 7 Lightning strikes to protected object (red colour)

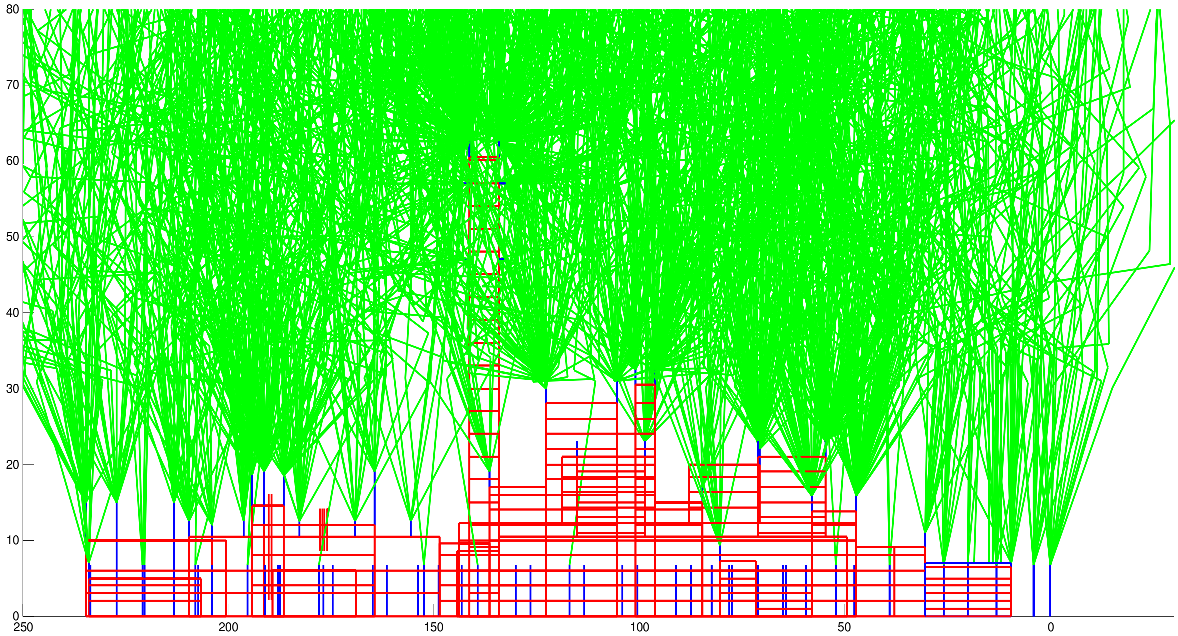


Figure 8 Lightning strikes to air-termination system (blue colour)

In this case the lengths and positions of the air-termination rods on objects 21 and 22 were corrected and simulations were carried out again. Finally, total of 60 air-termination rods with 2-3 m length above protected objects was selected to protect oil refinery. Object 1 was protected with mesh-conductors and down-conductors. Total of 10000 lightning strikes were simulated, of which 87257 hit ground, 1240 air-termination system and 3 oil refinery (Figs. 9 and 10). Since lightning strikes can hit only the middle part of the object 17 (with very low probability) which is not hazardous area, it can be concluded that air-termination system effectively protects the oil refinery.

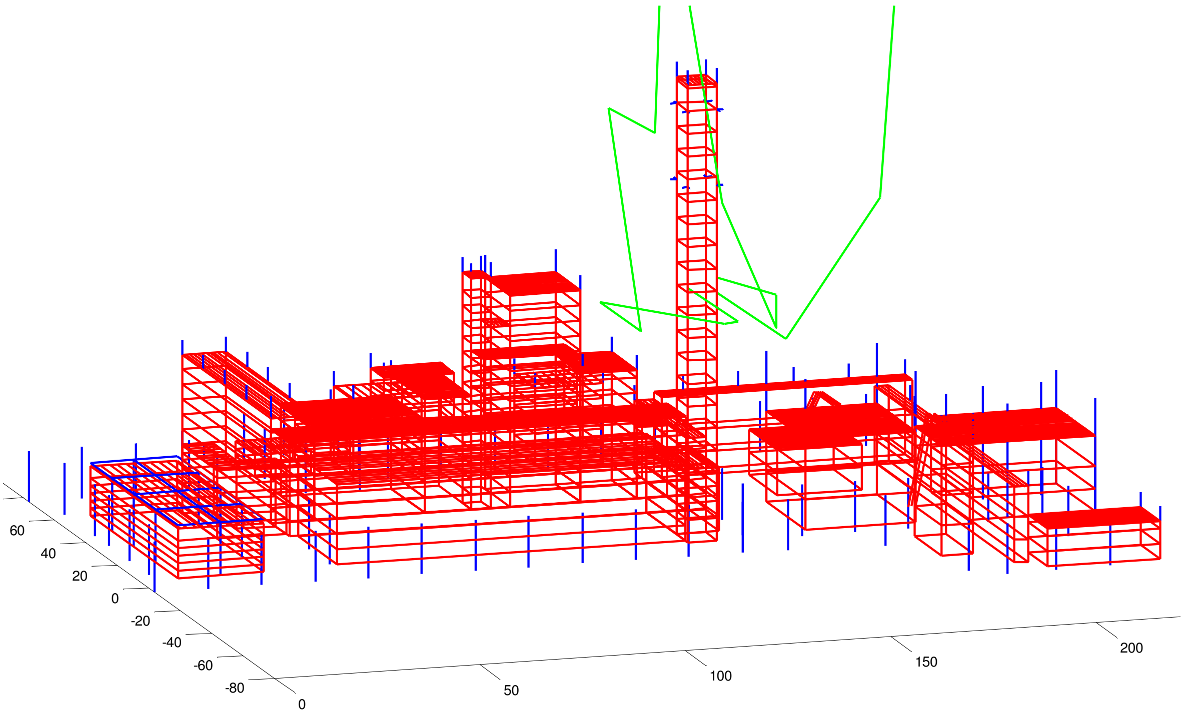


Figure 9 Lightning strikes to protected object 17

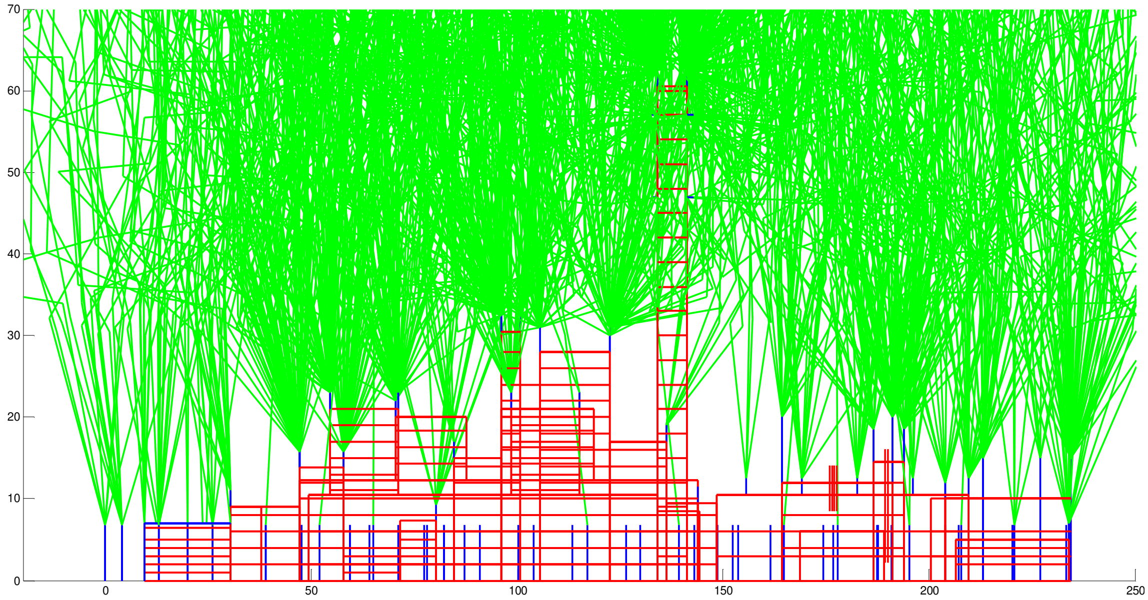


Figure 10 Lightning strikes to ait-termination system

On all structures higher than the rolling sphere radius *r*, flashes to the side of structure may occur. Each lateral point of the structure touched by the rolling sphere is a possible point of strike. However, the probability for flashes to the sides is generally negligible for structures lower than 60 m. For taller structures such as object 17, the major part of all flashes will hit the top, horizontal leading edges and corners of the structure. Only minor part all flashes will hit the side of the structure. Therefore a lateral air-termination system is installed on the upper part of the object 17 (the top 20 % of the height of the structure) [5].

5. APPLICATION OF LIGHTNING LOCATION SYSTEM DATA

Analysis shown in section 4 is based on lightning current parameters from [1], [5]. The lightning current parameters defined in IEC standards are mainly based on measurements by Berger and co-workers in Switzerland [2], [3]. These lightning parameters are still used to a large extent as the primary reference source for both lightning protection and lightning research. Fig. 11 shows the cumulative frequency of the current peak of the first negative stroke according to CIGRE.

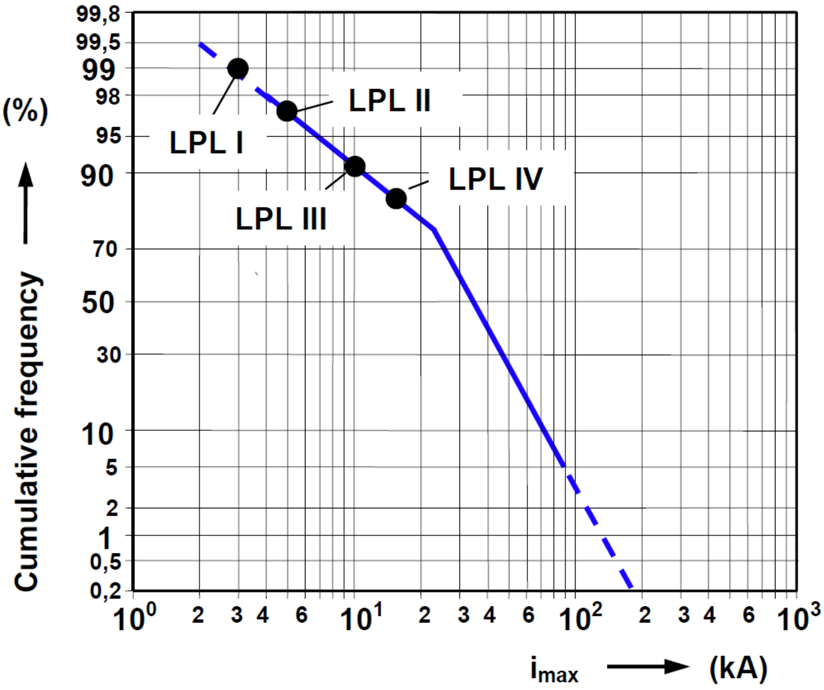


Figure 11 Cumulative frequency of the current peak of the first negative stroke according to CIGRE, ● fixed values in IEC 62305-1 for LPL I-IV

For example, for LPL II the rolling sphere radius equals *r*=30 m corresponding to the maximum current peak of 5 kA (Table I). It is accepted that 3 % of the lightning has smaller current peaks, while 97 % of the lightning has higher current peaks. This means that there is the residual risk that 3 % of the lightning may terminate at the object to be protected.

More recent direct current measurements were obtained from instrumented towers in Austria, Germany, Canada and Brazil, as well as from rocket-triggered lightning [6]. Further, modern LLSs report peak currents estimated from measured electromagnetic field peaks. The available technology for detecting and locating lightning to ground has significantly improved over the last decades. LLS data have the advantage of covering extended areas on a continuous basis and can therefore observe the related exposure of objects to the lightning threat.

Fig. 12 shows cloud to ground (CG) strokes around oil refinery for 5 year period. Data were obtained from Croatian LLS [7] which is capable of detecting multiple-stroke flashes where every stroke is represented by individual set of data (discharge time, location, current amplitude…). LLS is also capable of detecting CG discharges of low current amplitude. Table II shows number of detected strokes to oil refinery by type and polarity.

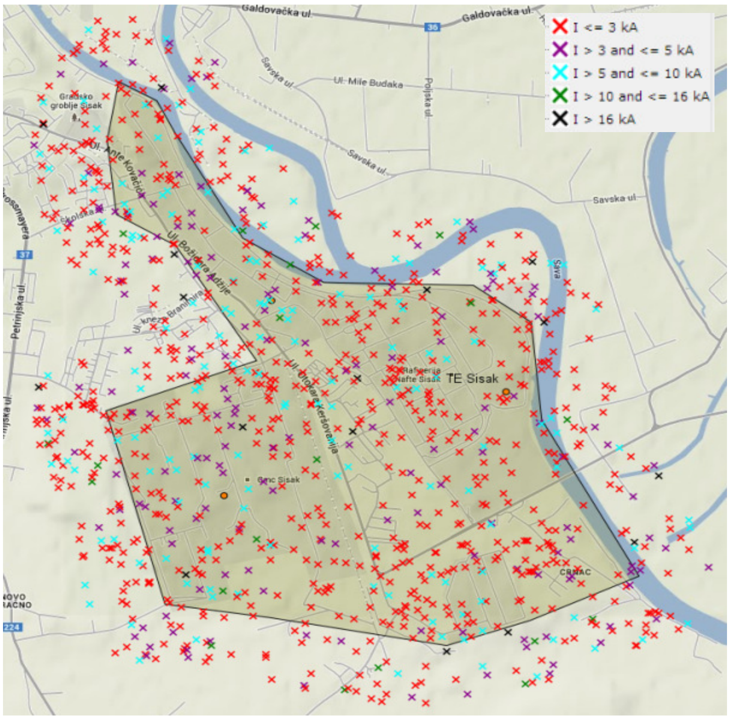


Figure 12 CG strokes around oil refinery for 5 year period

Table II No. of detected strokes to oil refinery by type and polarity

	Positive	Negative	All
CG	364	713	1077
IC	309	165	474
Total	673	878	1551

According to LLS data, 18.23 % of all CG negative strokes have current amplitudes lower than 5 kA. CG flashes usually consist of one or several strokes coming in very short temporal succession and close spatial proximity. The common method for converting stroke data into flashes is using the thresholds for maximum temporal separation and maximum lateral distance between successive strokes. For this purpose an algorithm for grouping lightning strokes into flashes (assessment of the lightning stroke multiplicity) was developed in order to determine the current probability distribution of the first CG strokes. The multiplicity is calculated for maximum temporal separation of 200 ms and maximum lateral distance of 2 km between successive strokes [8]. Table III shows number of first strokes (flashes) to oil refinery by type and polarity.

Table III No. of first strokes (flashes) to oil refinery by type and polarity

	Positive	Negative	All
CG	244	457	701
IC	229	124	353
Total	473	581	1054

When considering only negative CG flashes (all strokes in a flash of negative CG strokes type), 79.3 % are single stroke and the multiplicity was found to range between 1 and 13 with an average value of 1.54 strokes per flash. Table IV shows parameters of flash with the largest number of subsequent strokes (13 strokes). In this case the maximum inter stroke location difference equals 908 m and the maximum time difference 112 ms. The first stroke had the maximum current amplitude within complete flash (-50.6 kA) while the second highest amplitude was registered in the fourth subsequent stroke (-50.0 kA).

Table IV Parameters of registered flash with 13 strokes

Stroke No.	Time	Current Amplitude [kA]	Inter Stroke Time Difference [ms]	Inter Stroke Location Difference [m]
1	21:17:47,630	**-50.6**	-	-
2	21:17:47,648	-9.3	18	367
3	21:17:47,668	-15.3	20	50
4	21:17:47,712	**-50.0**	44	58
5	21:17:47,788	-40.9	76	37
6	21:17:47,886	-23.4	98	64
7	21:17:47,888	-8.6	2	822
8	21:17:47,945	-23.1	57	**908**
9	21:17:48,017	-10.1	72	258
10	21:17:48,068	-7.0	51	33
11	21:17:48,180	-11.3	**112**	100
12	21:17:48,211	-16.7	31	91
13	21:17:48,280	-8.2	69	100

Fig. 13 shows the maximum distance between successive strokes.

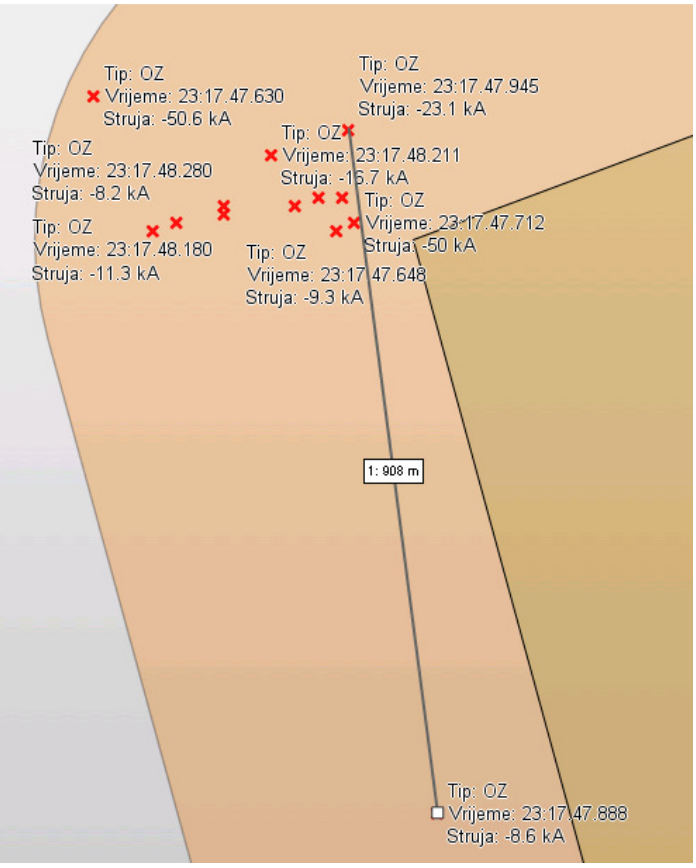


Figure 13 Maximum distance (908 m) between successive strokes

Fig. 14 shows cumulative frequency of the current peak of the first negative CG stroke according to LLS data.

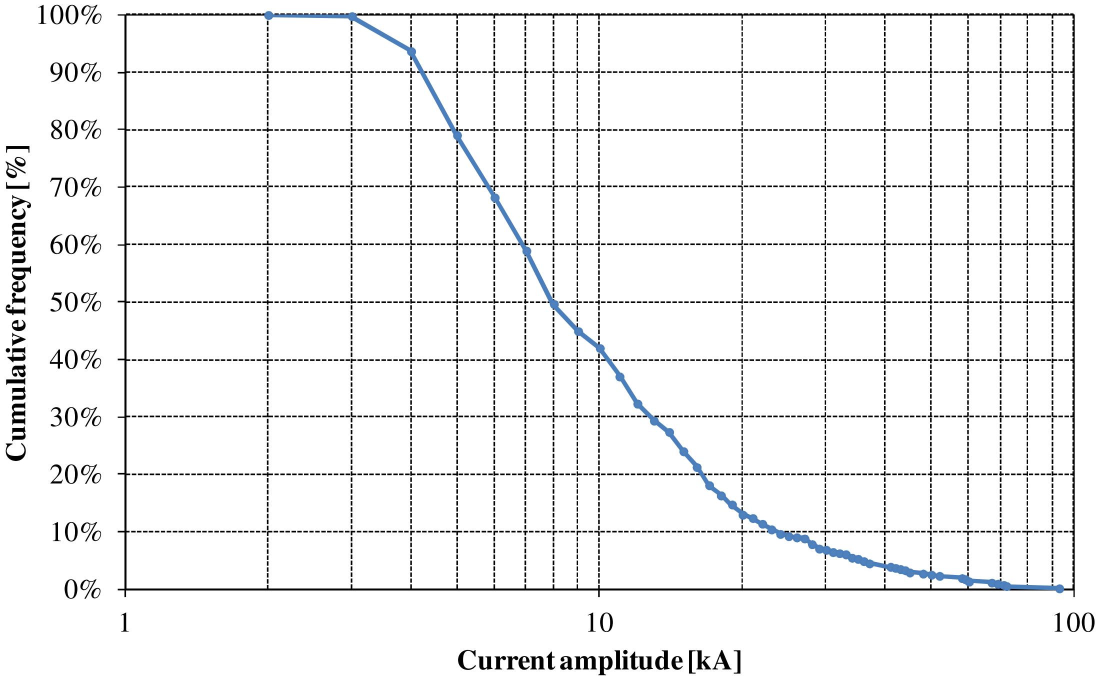


Figure 14 Cumulative frequency of the current peak of the first negative CG stroke according to LLS data

Comparison between LLS data (Fig. 14) and IEC 62305 data corresponding to LPLs I-IV is shown in Table V.

Table V Comparison between IEC 62305 and LLS data for first negative stroke

Lightning protection level LPL	Probability *p* where peak values of current are greater than the minimum values (IEC 62305)	Probability *p* where peak values of current are greater than the minimum values (LLS data)	Minimum peak value of current *I* (kA)
I	99 %	99.8 %	3
II	97 %	79.1 %	5
III	91 %	42.0 %	10
IV	84 %	21.3 %	16

Comparison regarding LPL I, with minimum peak current of 3 kA, shows similar results. Analysis of LLS data regarding LPLs II-IV indicate there is a significantly higher probability of low amplitude CG first strokes occurrence compared to the IEC standard. Consequently, the risk of the lightning terminating at the object to be protected is higher according to LLS data. However, some specific cases [9] indicate that very weak IC events with currents below 3 kA may be misclassified as CG strokes. This may slightly affect probabilities obtained by LLS data analysis.

6. CONCLUSION

The paper describes designing and positioning of air-termination system of oil refinery and analyzes the effectiveness of its external lightning protection system. The electro-geometric model was used to determine the optimal height and number of air-termination rods according to standard IEC 62305. The lightning parameters are essential input variables for estimating the effectiveness of external lightning protection system. Therefore, the lightning parameters used in IEC standard were compared to ones derived from lightning location system observations.

An algorithm for grouping lightning strokes into flashes (assessment of the lightning stroke multiplicity) was developed in order to determine the current amplitude probability distribution of the first CG strokes. The multiplicity was calculated for maximum temporal separation of 200 ms and maximum lateral distance of 2 km between successive strokes. Analysis of LLS data shows that there is there is a significantly higher probability of low amplitude CG first strokes occurrence compared to the IEC standard. Consequently, for a given lightning protection level, the risk of the lightning terminating at the object to be protected is higher.

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