

PROBABILITY OF LIGHTNING STRIKES TO AIR-TERMINATIONS OF STRUCTURES USING THE ELECTRO-GEOMETRICAL MODEL THEORY AND THE STATISTICS OF LIGHTNING CURRENT PARAMETERS

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ABSTRACT

Planning the air-terminations for a structure to be protected the use of the rolling-sphere method (electro-geometrical model) is the best way from the physics of lightning point-of-view. Therefore, international standards prefer this method. However, using the rolling-sphere method only results in possible point-of-strikes on a structure without giving information about the probability of strikes at the individual points compared to others.

Extending the electro-geometrical model using the probability distributions of natural lightning parameters, and implementing this idea into a numerical simulation computer code gives the possibility to show the different exposure of individual points of a structure to direct lightning strikes and with that the different “efficiency” of air-terminations at these points.

The results of the method described may help in the future, to optimize the planning of air-terminations due to their lightning strike capturing efficiency.

1 INTRODUCTION

Planning of air-terminations for structures is possible based on three methods given in international standards for lightning protection [1, 2]:

- rolling-sphere method (electro-geometrical model);
- derived from that: protective angle method;
- derived from that: mesh method for flat (roof) areas.

The rolling-sphere method is the basic planning procedure. This method is well-known since many years and has impressively shown its quality [3].

For different requirements for lightning protection systems (LPS) four lightning protection levels (LPL) are defined, and based on that finally four classes of an LPS (I – II – III- IV) [1, 2]. They differ regarding the rolling-sphere method in the rolling-sphere’s radius, which is fixed between 20 m and 60 m [1, 2].

With the fixed rolling-sphere radii different smallest peak values of natural lightning flashes are covered, i.e. lightning flashes with even smaller values than the fixed

one for the used rolling-sphere may strike a structure beside the air-terminations planned according to [2].

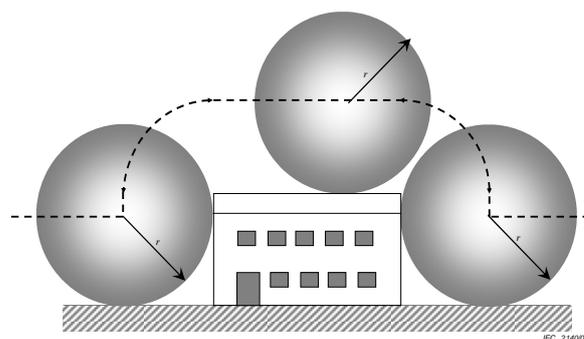


Figure 1: Structure to be protected with rolling spheres (radius r) – side view [2].

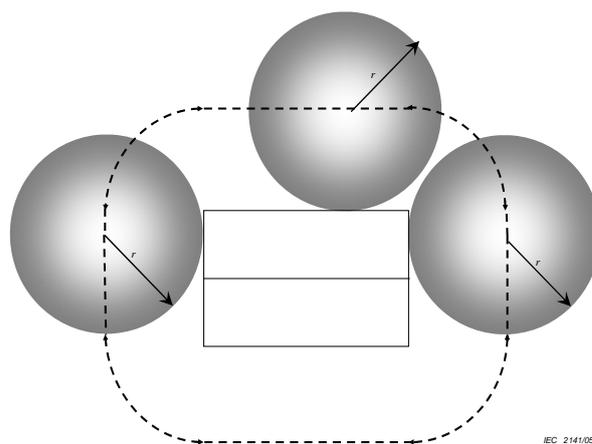


Figure 2: Structure to be protected with rolling spheres (radius r) – plan view [2].

Hence, planning with the rolling-sphere leads to the possible point-of-strikes, where air-terminations have to be placed. However, no information is contained, how probable lightning strikes at these individual different points are. If some planning examples are investigated (e.g. Fig. 1 & Fig. 2), one can easily recognize, that to each possible individual point-of-strike on a flat roof area always only one center point of a rolling-sphere can be linked, whereas at the roof's corners and edges the rolling-sphere can be "turned" by 90°.

As a result, to one possible individual point-of-strike at the roof's edge and especially at the roof's corner much more center points of possible rolling-spheres are aligned. However, based on the rolling-sphere method the flat roof as well as the roof's edges and corners are possible point-of-strikes, which had to be protected by air-terminations. This result is fixed without taking into account, that the strikes to edges and corners are essentially more probable. The method described in this paper takes into account this probability.

HARTONO and ROBIAH developed a so-called collection surface method (CSM) [4], which is generally the basis of the investigation described in this paper. However, the CSM still used fixed rolling-sphere radii, and with that does not consider the probability distributions of the lightning current peak values [1].

Another approach was given by METWALLY, HEIDLER and NICKEL [5]. They computed the striking probability to a structure on the basis of a numerical method, simulating the stepwise propagation of the downward leader from the cloud in direction to the structure. However, also this method used constant values of the final jump distance and with that of the rolling-sphere radii. Consequently, also in this method the probability distributions of the lightning current peak values were not implemented.

2 FUNDAMENTAL DATA FOR THIS INVESTIGATION

2.1 Probability distribution for lightning current peak values

Probability distributions for lightning current peak values are very well investigated. The actual so-called "CIGRE data" are the basis for international standards on lightning protection, the standard series IEC 62305:2006. Annex A of IEC 62305-1 [1] gives all necessary parameters for the analytical description of the density function as a lognormal distribution [6]:

$$f(I) = \frac{1}{\sqrt{2\pi} \cdot \sigma \cdot I} \cdot e^{-\frac{\left(\ln \frac{I}{\mu}\right)^2}{2 \cdot \sigma^2}} \quad (1)$$

- A) For a first approach only the distribution for negative first short strokes is used (curves 1A & 1B from [1], Fig. A.5), because this component contains 80 – 90% of natural lightning. The parameters for eq. (1) are given in Table 1.

Table 1: Parameters of the negative first stroke distribution [1]

Parameter for eq. (1)	$I < 20$ kA	$I > 20$ kA
Mean value μ [kA]	61	33.3
Logarithmic standard deviation σ	1.33	0.605

- B) Secondly additionally also the (few) positive short strokes, which normally show higher peak values (curve 3 from [1], Fig. A.5), are taken into account. Parameters for eq. (1) are given in Table 2.

Table 2: Parameters of the positive first stroke distribution [1]

Parameter for eq. (1)	
Mean value μ [kA]	33.9
Logarithmic standard deviation σ	1.21

- C) Finally the individual distributions for negative (A) and positive (B) short strokes are combined, using the ratio 90%/10% according to [1].

Besides the IEC/CIGRE data there are also other possible descriptions of the lightning current parameters (e.g. data provided by IEEE [7]). To avoid possible confusion and discussions about this, those other descriptions are not considered in this investigation. We use only the description which is internationally accepted [1] and based on long-term measurements of different research groups. However, it should be mentioned, that generally also other lightning current descriptions could be used for the presented procedure.

2.2 Electro-geometrical model

Based on the electro-geometrical model to each lightning current peak value I a length of the final jump and with that the rolling-sphere radius r can be linked. Enormous research work on this subject was performed, for instance again in the frame of CIGRE. Nowadays, the following description is given, used especially in international lightning protection standards [1]:

$$r / m = 10 \cdot \left(\frac{I}{kA} \right)^{0.65} \quad (2)$$

Over the years also more relations of rolling-sphere radii and lightning current peak values are published from different research groups worldwide; a good

overview is given in [3]. This is especially valid for elevated structures, where the attachment process is clearly different from that for (flat) objects on the ground.

However, similar to what is said for the lightning current description (chapter 2.1), for this investigation only the relation given by eq. (2), which is internationally accepted [1] and based on long-term measurements of different research groups, is used. Nevertheless, generally also other relations could be used in the procedure.

With eq. (2) the three distributions for the lightning current peak values A, B, and C can be transformed into three distributions for the length of the final jump or the rolling sphere radius r . Fig. 3 gives the density functions for a certain radius r , Fig. 4 the cumulative frequency distributions for a radius r covered by the given value, again called A, B, and C (A: negative first strokes only; B: positive first strokes only; C: negative and positive first strokes combined using the ratio 90%/10%).

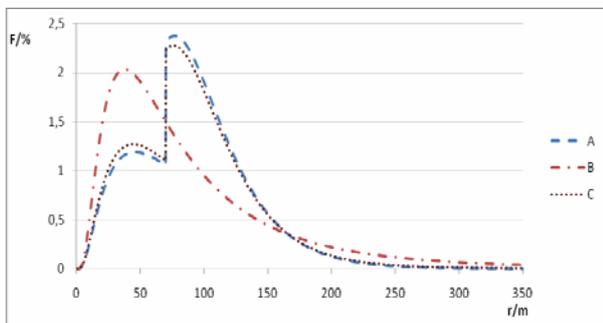


Figure 3: Density functions $F(r)$ for the rolling sphere radius r based on the lightning current peak value descriptions of chapter 2.1.

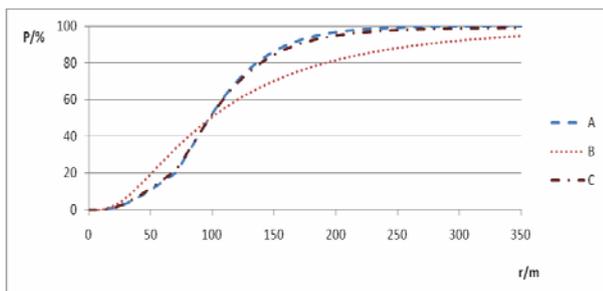


Figure 4: Cumulative frequency distribution function $P(r)$ for radius r based on the lightning current peak value descriptions of chapter 2.1.

As expected, the distributions A and C show no significant differences. Of course, distribution B differs somewhat, due to the generally higher current peak values of the positive short strokes. In chapter 4.3 an additional calculation is performed, showing the practical influence of the three different distributions on the striking probability.

Independent from that, generally distribution C is chosen for the next stages of the investigation, due to the facts, (1) that it is based on the standardized description of lightning parameters [1], and (2) that it takes into account negative and positive first short strokes.

3 NUMERICAL APPROACH

3.1 Discretization

The entire surface of the structure to be protected including any air-terminations (e.g. rods) has to be described, as well as the ground surrounding the structure. For that the surface of the structure is discretized areally (surface points). The space outside the structure (above and besides) is discretized spacially (space points). Using simple geometrical relations or equations, resp., for each space point the closest surface point can be defined.

The distance between space point and surface point is the final jump distance and with that the rolling-sphere radius. For this radius or the relevant radius interval (as a result of the spacial discretization) according to eq. (2) an interval of the lightning current peak value can be linked and with that finally a probability value for a lightning strike from that space point to the surface point considered.

In this context it must be mentioned, that only the pure geometrical distance between the space point and the surface point is determined. Any electric field enhancement effect is disregarded, because these effects are assumed to be valid only in the close vicinity to exposed surface points. With that, those enhancement effects do not influence remarkably the starting process of the final jump, at least for flat objects on the ground. However, if such an influence should be considered, it will further improve the “efficiency” of corners and edges, as well as especially of lightning rod tips.

The steps mentioned above are conducted generally for all space points. Then all probability values for the individual surface points are added and finally normalized to a total probability of 100% for a lightning strike to the entire structure.

3.2 Computer code

For the numerical solution a discretization of the problem is required. Therefore we have three independent discretizations.

Firstly the geometry of the structure to be considered and its air-terminations. This and the surrounding ground are discretized areally in a predefined discretization distance (surface points = SuP).

Secondly the space outside the structure - above and besides - is discretized spacially also in a predefined discretization distance (space points = SpP).

The third discretization is performed for the final jump

distances (intervals of the rolling-sphere radii) and with that for the intervals of the lighting current peak values.

After the numerical calculation is performed, for all surface points their individual probability value for a lightning strike is shown. Additionally, also the largest possible rolling-sphere radius still touching an individual surface point is determined; with that the highest possible lightning peak current at this surface point can be given.

Fig. 5 gives a fundamental flow diagram of the computer code.

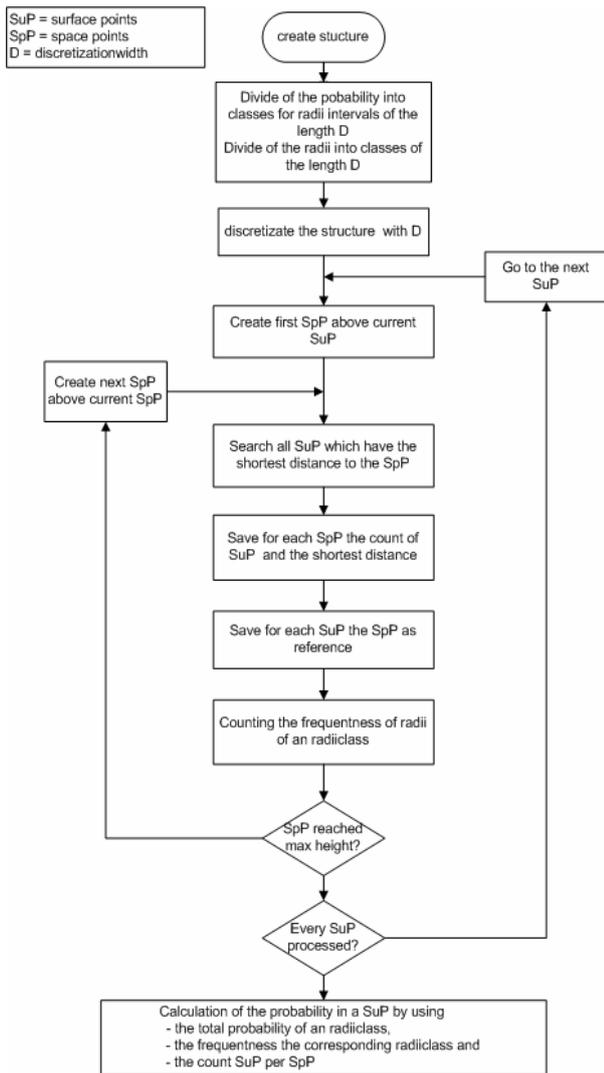


Figure 5: Fundamental flow diagram of the computer code.

4 BASIC EXAMPLES AND RESULTS

4.1 Definition of reference structures

Firstly, for the further numerical investigations three reference structures are defined:

- I) Simple structure with an area of 40m x 40m and a height of 10m;
- II) As I above, with four rods (height 4m) at the corners;
- III) As I above, with one rod (height 10m) in the roof's center.

The numerical investigations are generally performed with a discretization interval (surface points and space points) of 2m. The space points are filled until 300m above and 200m besides the reference structure. Generally, the lightning current peak value distribution C given in chapter 2.1 is used.

4.2 Basic results

Fig. 6 shows the structure I without any LPS or with a meshed flat air-termination network according to [2] (the existence of such an air-termination system does not influence the striking probability on the roof). It is shown, that the combined probability of a lightning strike to all four corners is approx. 46% (each corner 11.5%). According to the planning procedure using the rolling-sphere [2] the entire roof has to be protected equally against lightning strikes. However, fig. 6 demonstrates, how different the striking probabilities are on the flat roof areas, the roof edges, and the roof corners.

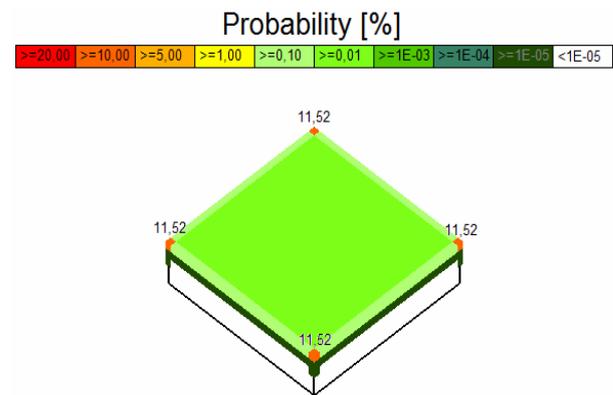


Figure 6: Probability of strikes to the structure I (flat roof 40m x40 m, 10m height) without further air-terminations.

Fig. 7 represents structure II, being the structure I protected with air-termination rods at the 4 corners with a height of 4m. The combined probability of a lightning strike to all four rod tips is approx. 99% (each rod has 24.7%). Compared to fig. 6 one can recognize the high efficiency of the 4 rods, which nearly perfectly protect the entire roof: an LPS capturing 99% of all lightning

strikes fulfils the requirements of the lightning protection level I [1] and with that could be classified as an LPS class I [2]. In addition to that, it should be mentioned, that the higher the peak current values, the more efficient the four rods work, i.e. only small peak currents with only a weak “damaging effect” are able to strike the structure on the flat roof area between the rods.

Assuming an LPS class I (rolling-sphere radius 20m) and applying the standardized rolling-sphere planning procedure [2], for the structure II in fig. 7 the rolling-sphere touches the flat roof area starting from distances of 12m from each air-termination rod at the corner. Consequently wide areas of the roof (approx. 1200m², which represent 75% of the entire roof area) would have to be protected using additional air-termination rods or wires, even if the probability of a strike to these additional air-terminations is only approx. 1%. Exactly this information is missing, using the “classical” planning procedure with the rolling-sphere.

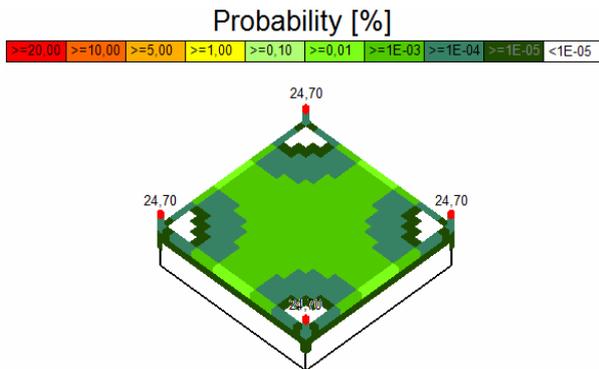


Figure 7: Probability of strikes to the structure II (flat roof 40m x 40m, 10m height) with four air-terminations rods (4m height) at the corners.

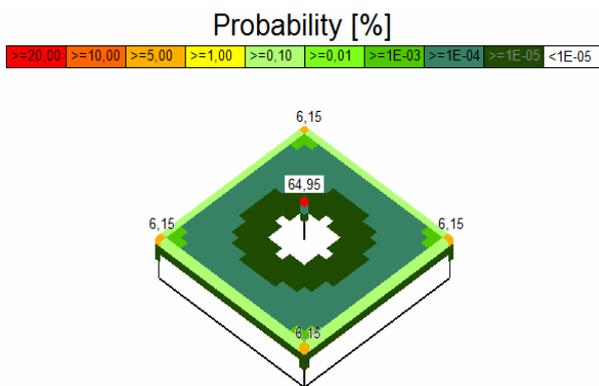


Figure 8: Probability of strikes to the structure III (flat roof 40m x 40m, 10m height) with one air-terminations rod (10m height) in the center of the roof.

Fig. 8 shows structure III, being structure I protected with only one lightning rod in the center of the roof. Even if the rod is comparatively high (10m), the probability of a lightning strike to the rod’s tip is only approx. 65%. The four corners of the structure still have a combined probability of approx. 24% (each corner 6.1%). Taking both locations together (rod’s tip and the four corners), we get a probability of 89%, i.e. only approx. 11% of all strikes occur on the flat roof and especially on the roof edges.

4.3 Influence of different lightning current peak value distributions

As mentioned already in chapter 2.2, for the three reference structures the influence of the different distributions A, B, and C of the lightning current peak values according to chapter 2.1 is further investigated. Calculated are the probabilities at different locations dependent on the three lightning current distributions. The following results for the probabilities at the interesting locations are given:

- Structure I: combined probability at the four roof corners (Table 3);
- Structure II: combined probability at the four rod tips (Table 4);
- Structure III: probability at the center rod’s tip and combined probability at the four roof corners (Table 5).

Table 3: Influence of the lightning current peak value distribution on the strike probabilities for structure I

Lightning current distribution	A	B	C
Combined probability at the four roof corners	45.8%	48.5%	46.1%

Table 4: Influence of the lightning current peak value distribution on the strike probabilities for structure II

Lightning current distribution	A	B	C
Combined probability at the four rod tips	98.9%	98.1%	98.8%

Table 5: Influence of the lightning current peak value distribution on the strike probabilities for structure III

Lightning current distribution	A	B	C
Probability for the center rod’s tip	64.2%	71.5%	64.9%
Combined probability at the four corners	25.3%	18.4%	24.6%

There is only little influence of the chosen distribution on the strike probabilities. Distribution A and C show only differences in the range of a few tenth of a percent, whereas distribution B differs by a few percent. However, distribution B covers only the (few) positive short strokes.

Therefore, as already mentioned, for all further examples of this investigation, only distribution C is used, covering both negative and positive first short strokes in the ratio given by international standards [1].

4.4 Influence of the lightning rod's height

Finally the influence of the lightning rods' height is investigated numerically. The height is varied:

- for structure II between 0 and 10m for all four rods equally (Fig. 9);
- for structure III between 0 and 20m (Fig. 10).

As can be recognized in Fig. 9, the probability of a strike to the four corners immediately increases with only a small height of rods positioned there. If the rods have a height of 2m, almost 95% of lightning flashes will strike them. With a rods' height of approx. 4m nearly all flashes are captured, only approx. 1% of all the strikes are to the remaining parts: the flat roof and the roof edges. Therefore, a further increase of the rods' height shows only little improvement.

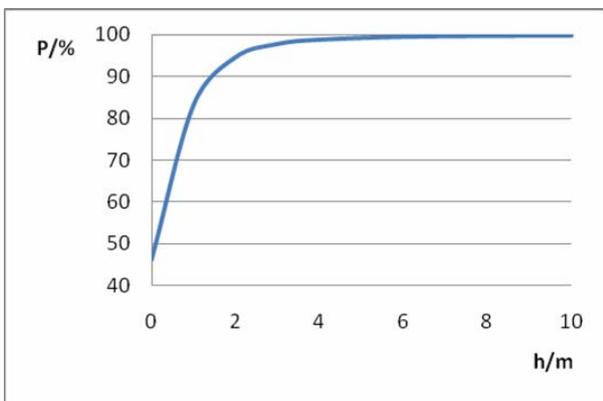


Figure 9: Structure II - Combined probability P of strikes to the four rods depending on their height h .

A single rod in the center of the roof is not comparably efficient (Fig. 10). A probability of 50% is reached, if the rod's height is approx. 8m. And even if the rod has a height of (unrealistic) 20m, the probability is "only" in the range of 95%. However, if also the corner strikes are taken into account, we get a much better behaviour. If, in addition to a 10m high rod in the center, the corners are protected with only little rods, the combined probability is in the range of 91%, with that fulfilling the interception efficiency of an LPS class III [2].

A general result however is, that protecting the corner of a roof with (little) rods is usually more efficient than only using a single (high) rod in the roof's center.

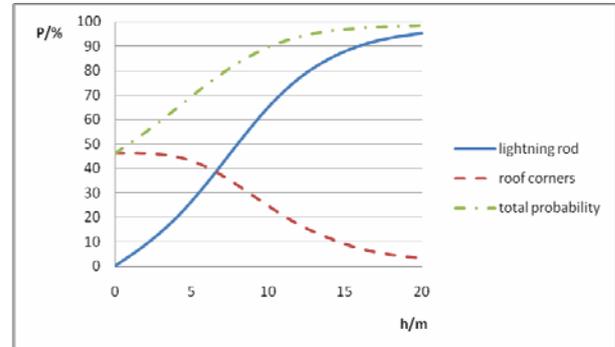


Figure 10: Structure III - Probability of strikes P to the rod depending on its height h and remaining combined probability of strikes to the four roof corners.

5 APPLICATION OF THE METHOD TO A MORE COMPLEX STRUCTURE

The method is, of course, also applicable on arbitrary complex structures. As an example the following building is investigated (Fig. 11). The figure shows the geometry of the structure (lengths, widths, and heights), as well as the probabilities at the most vulnerable points of this building, usually at the corners of the individual roofs, without any lightning protection measures.

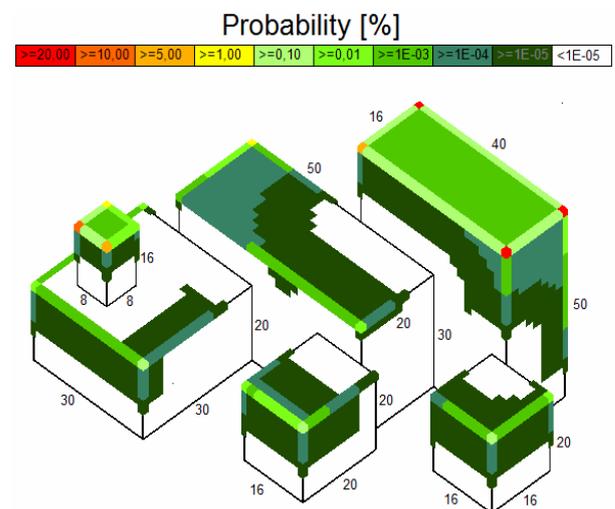


Figure 11: Example of a complex structure.

It is assumed, that an LPS class III is to be installed. Based on [1] such an LPS must have an interception efficiency of at least 91%, i.e. 91% of all possible lightning strikes must be captured by the air-terminations.

Fig. 12 shows a possible solution for this case. The given eight rods (four on the highest block of the structure in the back, four on the “roof protrusion” in the front, height 2m) catch about 94% of all strikes.

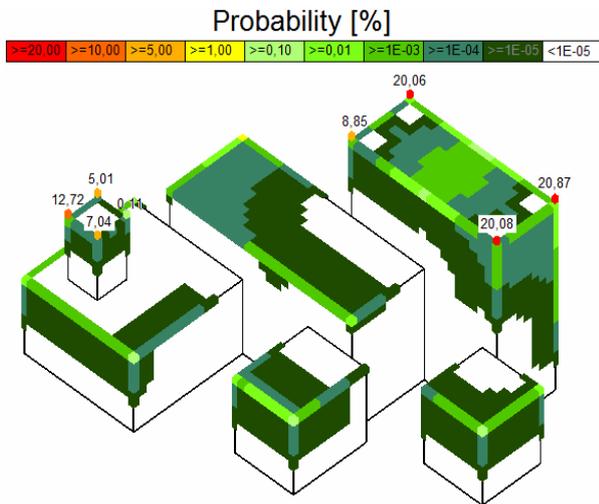


Figure 12: Example of air-terminations for the complex structure to comply with the basic requirements of an LPS class III – Probabilities of strike.

Fig. 13 finally shows the maximum lightning current peak values which may strike the structure at the different parts. Here, essentially the unprotected parts of the structure are of interest. It can be clearly observed, that only comparatively “small” lightning flashes strike besides the air-terminations, and these flashes will have only a low “damaging effect”.

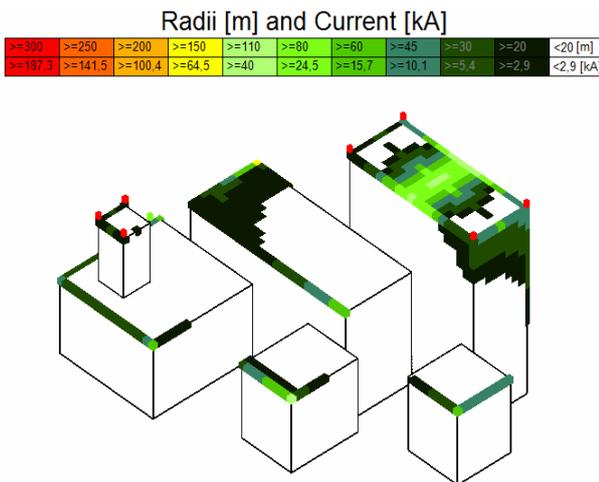


Figure 13: Example of air-terminations for the complex structure to comply with the basic requirements of an LPS class III – Maximum rolling-sphere radii and maximum lightning peak currents at the different parts of the structure.

Using the information given in fig. 12 and fig. 13, one can easily further improve the interception efficiency of the air-termination system. Four additional rods for the four still unprotected corners of the structure, where the probability exceeds the value 0.1%, and two additional rods for the central axis of the highest block of the structure in the back, where still lightning strikes with current peak values of $> 40\text{kA}$ are possible, will lead to an interception efficiency of more than 99%, with that fulfilling the appropriate requirement of an LPS class I [2].

6 CONCLUSIONS

The numerical method presented in this paper uses existing and internationally accepted data, relations and investigations. Based on that, a numerical method is established giving the real probabilities of lightning strikes to different points on the surface of a structure. As supposed, the edges and corners of the structures are more exposed than flat surfaces. The tips of slim roof protrusions (e.g. rods) are even more endangered.

It is shown, that with a comparatively small number of rods a highly efficient air-termination system can be installed. Compared with the standard procedure of placing rods on roofs (and walls) described in [2], the rolling-sphere method, the number of rods can be much smaller. Reason is the fact, that the rolling-sphere method is very conservative, giving the planner all possible point-of-strikes without providing directly an information about the probability of such a strike. This means on the other hand, that planning air-termination rods with the rolling-sphere method is on the safe side; the interception efficiency of such an LPS is (much) higher than given in [1], a fact, which is already mentioned in the literature (e.g. [3]).

However, if a risk analysis according to [8] leads to a clearly defined necessary reduction of the damage probability to a structure caused by direct strikes, i.e. a necessary “efficiency” of an external LPS, the use of the presented method may lead to sufficient results without a severe oversizing.

The method presented allows also to take into account the influence of adjacent, surrounding structures on the probability of a lightning strike to an investigated structure. With that for example the location factor C_d in the risk analysis [8] can be estimated more in detail.

It must be mentioned, that the investigation here is only focusing on air-terminations of an LPS. An LPS, of course, usually has more tasks to fulfill. So for example the need for equipotentialization, for current sharing and for reducing magnetically induced voltages may lead to further requirements also for the air-termination system.

Finally, the results of this investigation may lead to a better understanding, how non-conventional air-terminals (e.g. ESE - early streamer emission) “work”. ESE

proponents argue, that a huge number of these devices is installed, and there are only a few interception failures (e.g. published in [9]); hence, the method works. However, the obviously small number of interception failures of ESE devices is absolutely clear, looking at the results presented in this paper, and this is not a consequence of any “lightning triggering effect” of such devices. Rods have always a significant capturing effect on downward leaders, independent if these are ESE devices or simple Franklin rods [3].

As a consequence, replacing ESE devices by Franklin rods with the same dimensions (height) would lead to similar “good results” of their behaviour: a high number of lightning strikes occurs to the rod’s tip (let us say, 80%), and the other 20% have comparatively low current peak values, so that their remaining “damaging effect” on or at other parts of the roof is low. This is essentially also the opinion of the international scientific community and the background for international standardization of lightning protection. Therefore, in the 2nd Edition of IEC 62305-3 [10] it will be stated: “For all types of air terminals only the real physical dimensions of the metal air-termination systems shall be used for the determination of the volume protected.”

7 REFERENCES

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