Calculation of interception efficiencies for air-terminations using a dynamic electro-geometrical model

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Abstract - **The paper firstly presents the method of a dynamic electro-geometrical model. In contrast to the classic rolling-sphere it does not use fixed radii, it works with a varying radius. The method only uses existing and in international standards accepted results, fundamentals of lightning physics, and investigations; on that base a numerical method is elaborated.**

Using the dynamic electro-geometrical model, secondly some examples of protection with air-termination rods planned with the classic rolling-sphere according to IEC 62305-3 and for the classes of protection I – II – III – IV are investigated. It is shown, that the interception efficiencies are much higher than documented in the standard series IEC 62305. Reason is, that the method of the rolling-sphere is conservative, and that it gives the planner of lightning protection systems only the points, where lightning may strike, but without a rating with a striking probability. On the other hand this result clearly indicates, that using the classic rolling sphere method one is always on the "safe side".

Keywords: Lightning protection system, air-termination, IEC 62305, electro-geometrical model, numerical method, interception efficiencies

I. INTRODUCTION

The rolling-sphere method is the basic planning procedure for air-terminations of common structures. It is perfectly based on the physics of lightning, it has impressively, worldwide and since decades shown its quality, and it is fixed in international lightning standards, e.g. the modern standard series IEC 62305 [1, 2]. The scientific background of the method is the so-called electro-geometrical model [3].

For different requirements for lightning protection systems (LPS) four lightning protection levels (LPL) are defined, and based on that finally four classes of a 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.

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].

Consequently, planning with the rolling-sphere leads to possible point-of-strikes, where air-terminations have to be placed (Fig. 1 & Fig. 2). However, no information is contained, how probable are lightning strokes at these individual different points. One may take as an example a rectangular building with a flat roof. It is absolutely clear, that the probability of strokes is much higher at the edges and corners compared to the roof. However, according to the rolling-sphere method the flat roof as well as the roof's edges and corners are possible point-of-strikes, and with that they have to be protected by air-terminations. Hence, the "classical" rolling-sphere method does not directly provide a value of an interception efficiency at the different point-of-strikes.

On the other hand, detailed risk analysis according to IEC 62305-2 [4] needs to assess a probability, that a structure's external lightning protection system is effective against direct strokes, i.e. protects a structure sufficiently. Therefore also the knowledge of the interception efficiency of the air-terminations is useful and important.

HARTONO and ROBIAH developed a so-called collection surface method (CSM) [5], 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].

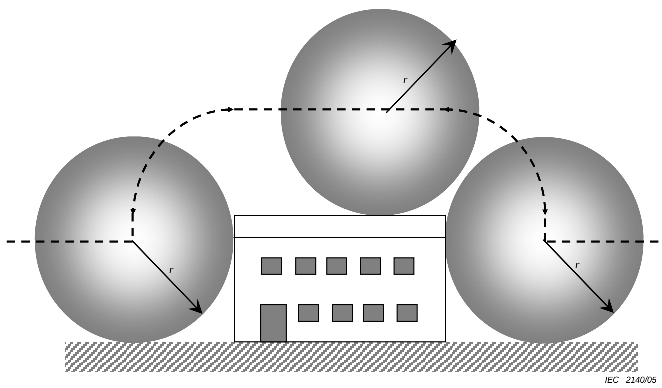

Figure 1. Structure to be protected with rolling spheres (radius r) – side view [2].

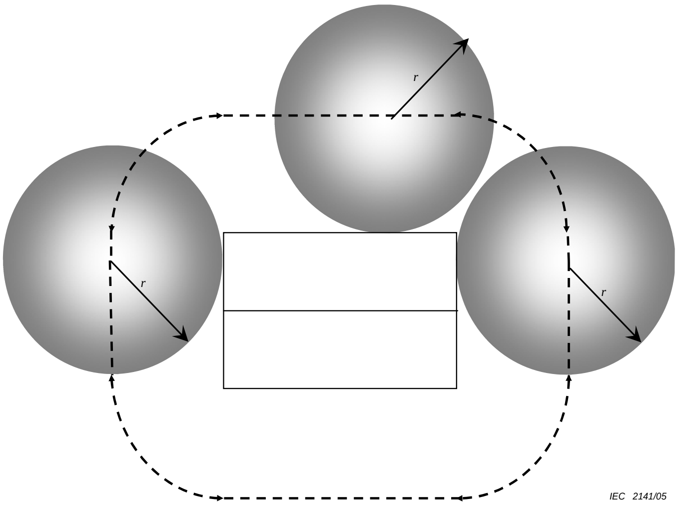

Figure 2. Structure to be protected with rolling spheres (radius r) – plan view [2].

The method described in this paper, which is strongly based on the electro-geometrical model, does not work with fixed rolling-sphere radii. In fact the radii are varied, therefore we call it dynamic electro-geometrical model. With this method a detailed calculation of interception efficiencies for air-terminations is possible. The following well-known fundamentals of lightning physics and simple geometrical considerations are combined to a numerical method [6]:

- The probability distribution for lightning current peak values of natural lightning, given in IEC 62305-1, Annex A, Figure A.5 [1], which allows to give a probability value, that a natural first lightning stroke has at least the dedicated peak value.
- 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, according to IEC 62305-1, Annex A [1].
- The entire surface of the structure to be protected including the air-terminations (e.g. rods) is discretized areally (surface points - SuP).
- The space outside the structure (above and besides) is discretized spacially (space points - SpP).
- To each space point the closest surface point is defined using simple geometrical relations. The distance between space point and surface point is the final jump distance. With that a probability value for a lightning stroke from that space point to the surface point considered can be assessed.
- The investigation of the closest surface point is performed generally for all space points.
- The probability values for the individual surface points are added. As we investigate under the assumption of a lightning stroke to the structure, every value finally is normalized to a total probability of 100% for a lightning stroke to the entire structure.

In the paper the dynamic electro-geometrical model is described in detail, and the results are discussed for some typical examples. The air-terminations of these typical examples are dimensioned according to the rolling-sphere method in IEC 62305-3 [2] for the four classes of a LPS (I – II – III- IV). Linked with these classes are interception efficiencies given in the standard series IEC 62305. For the typical examples the dynamic electro-geometrical model is applied, to calculate the real interception efficiencies in detail. Finally the calculated real interception efficiencies and the values given in the standard series IEC 62505 are compared.

It should be mentioned, that air-terminations can not always and for all cases be planned and installed purely based on the criteria of the interception efficiency. A LPS has to fulfil also other requirements, hence it is called a “system”. So for instance to improve the equipotentialization, the current distribution or the magnetically induced voltages in induction loops, the installation of further air-terminations may be required.

II. The Dynamic Electro-Geometrical Model

A. *Probability distributions 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. IEC 62305-1, Annex A [1] gives all necessary parameters for the analytical description of the density function as a lognormal distribution:

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

For the investigation, the negative and the positive first strokes have to be considered. The parameters for the negative first strokes described via (1) are given in Table 1, for the positive first strokes in Table 2.

TABLE I. Parameters of the negative first stroke distribution.

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

TABLE II. Parameters of the positive first stroke distribution.

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

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

B. 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. Nowadays, the following description is given, again used in the international lightning protection standard series IEC 62305 [1]:

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

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, for this investigation only the relation given by (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.

Using (2) the distributions for the lightning current peak values can be transformed into 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. The following abbreviations are used:

- A: negative first strokes only;
- B: positive first strokes only;
- C: negative and positive first strokes combined using the ratio 90%/10%.

Of course, for the dynamic electro-geometrical model and therefore also for the next stages of this investigation, only distribution C is used, due to the facts, that it is based on the standardized description of lightning parameters [1], and that it takes into account negative <u>and</u> positive first short strokes.

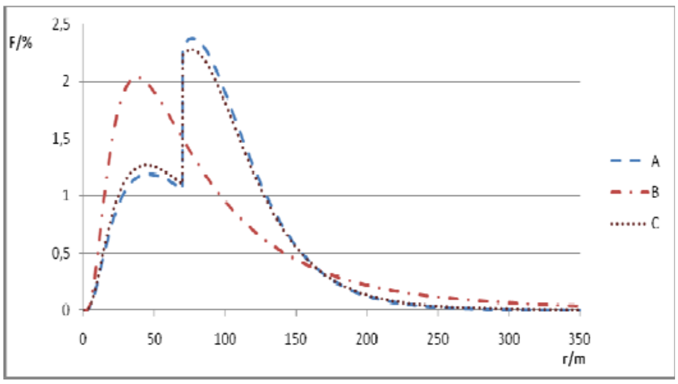

Figure 3. Density functions F(r) for the rolling sphere radius r based on the lightning current peak value descriptions, given in [1].

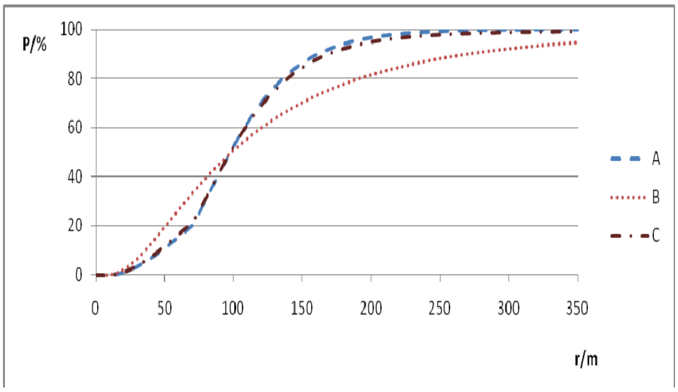

Figure 4. Cumulative frequency distribution function P(r) for radius r based on the lightning current peak value descriptions, given in [1].

C. Numerical procedure

The entire surface of the structure to be protected including any air-terminations (e.g. rods) has to be discretized areally, as well as the ground surrounding the structure (surface points - SuP). A discretization distance of a few meter is usually sufficient. However, in special cases (e.g. heights of air-termination rods of only some 10 cm – see Table III) a much finer discretization distance is necessary.

The space outside the structure (above and besides) is discretized spacially (space points - SpP).

Using simple geometrical relations or equations, resp., for each space point the closest surface point can be found. 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 (2) an interval of the lightning current peak value can be linked. With that finally a probability value for a lightning stroke from that space point to the surface point considered can be given. The steps mentioned above are conducted generally for all space points.

One surface point can be the closest one to different space points (with different radii). Therefore for each surface point all probability values which were calculated for it must be added. The sum of those is the final probability that lightning will strike there. If one space point has two or more surface points with similar distance, the probability of a stroke to one of these surface points is distributed equally.

As the last step, the sum of the probabilities to all surface points is normalized to the total probability of 100% for a lightning stroke to the entire structure.

In this context is must be mentioned, that only the pure geometrical distance between the space point and the surface point is determined. Any electric field enhancement effect at exposed points of the structure (e.g. air-termination tips, corners of the structure) 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 would only further improve the “efficiency” of corners and edges, as well as especially of lightning rod tips. This would further increase the already high values of the interception efficiency at those surface points. Hence, the approach of the dynamic electro-geometrical model can be assumed to be conservative.

The dynamic electro-geometrical model can be applied for arbitrarily complex structures [6]. An example gives Fig. 5, showing 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.

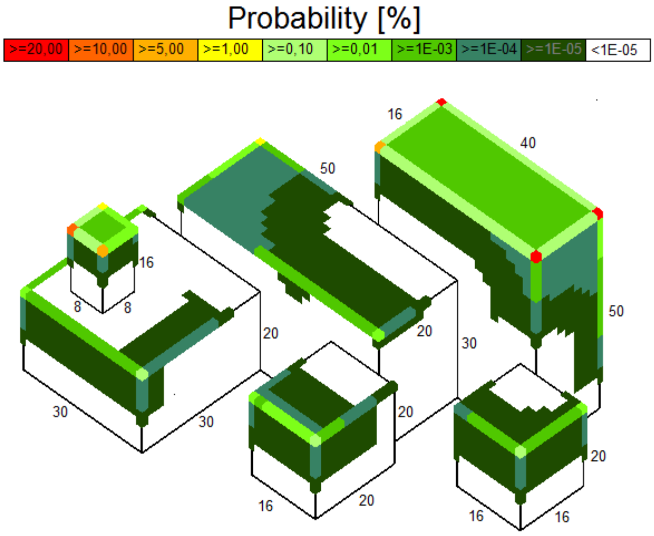

Figure 5. Example of a complex structure.

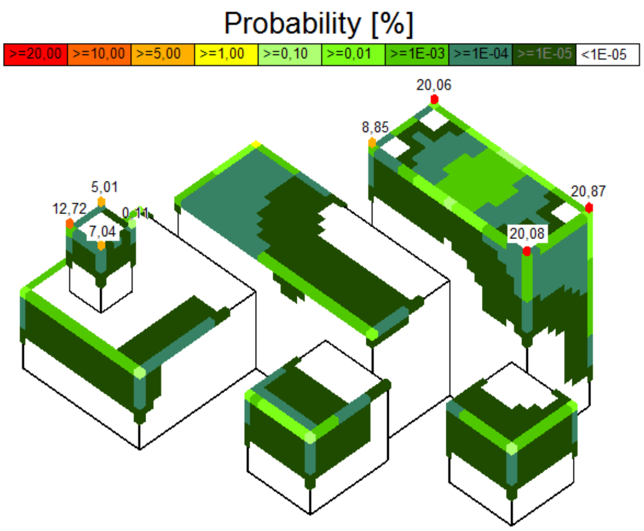

Figure 6. Example of a system of eight air-terminations rods for the complex structure catching about 94% of all strokes – Interception efficiencies.

It is assumed, that a LPS class III is to be installed. Based on [1, 4] such a LPS must have an interception efficiency of at least 91%, i.e. 91% of all possible lightning strokes must be captured by the air-terminations. Fig. 6 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 strokes.

III. Dimensioning of the Air-Termination Rods for the Reference Structure

The further investigations are based on a simple structure with a flat and quadratic roof area of 40m x 40m and a height of 10m. For this roof a protection with air-termination rods should be installed. The class of the LPS (I – II – III – IV) or the associated radii *r* of the rolling-sphere (20m – 30m – 45m – 60m), resp., and the distances *d* of the air-termination rods (5m – 10m – 20m – 40m), arranged in quadrates are varied. The necessary height *h* of the air-termination rods is a result of the maximum penetration distance *p*:

$$p = r - \sqrt{r^2 - \frac{d^2}{2}} \tag{3}$$

with: *r* radius of the rolling-sphere (= length of the final jump);
d distance of the air-termination rods (= side length of the quadrates built by the rods).

Please note, that *d* is the side length of the quadrates built by the rods, whereas for the maximum penetration *p* the diagonal of the quadrates must be considered. If no roof systems have to be protected, we may assume: *h* = *p*. Fig. 7 shows an example for this arrangement of air-termination rods.

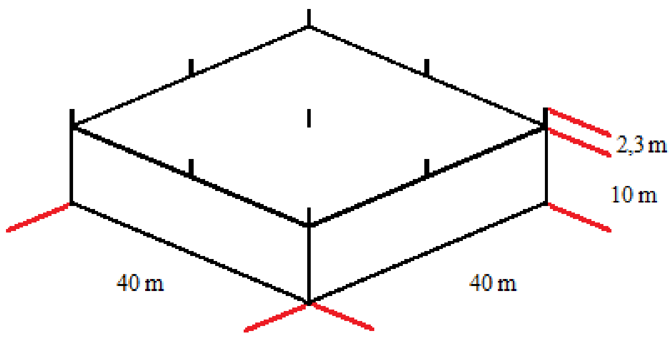

Figure 7. Nine air-termination rods as protection of the flat roof for LPS class III (*d* = 20m) – necessary minimum height *h* = 2,3m.

Table III displays the minimum heights of the air-termination rods, which are necessary for the individual combination of the LPS class (or rolling-sphere radius, resp.) and the rod's distance. The case of a LPS class I using only four air-termination rods (i.e. *d* = 40m) does not fulfil the standard requirements; consequently it is missing in Table III.

Additionally Table III gives the interception efficiencies W_1 for the individual classes of a LPS, which follow from IEC 62305-1 [1]. Indeed, this part of the standard series does not define interception efficiencies directly. However, they are given indirectly via the so-called "minimum values of lightning parameters".

TABLE III. MINIMUM HEIGHTS H [IN M] DEPENDING ON THE CLASS OF THE LPS OR THE RADIUS OF THE ROLLING-SPHERE, RESP., AND THE DISTANCE D OF THE AIR-TERMINATION RODS

LPS class	**Rolling -sphere radius *r* [m]**	**Distance of air-termination rods *d* [m]**				**Interception efficiency [1, 4] W_1 [%]**
		5	**10**	**20**	**40**	
I	20	0,3	1,3	5,9	-	99
II	30	0,2	0,9	3,6	20	97
III	45	0,15	0,6	2,3	10	91
IV	60	0,1	0,4	1,7	7,1	84

A lightning protection system may fail in two different directions:

- The sizing efficiency documents, that components of the LPS may be overloaded, if certain parameter values of lightning currents are exceeded. Hence, the components may be damaged or even destroyed. This happens in case of very high lightning current parameters. Therefore a set of maximum values of lightning parameters is fixed in IEC 62305-1 [1] for each LPL.
- With the interception efficiency it is intended to demonstrate, that a LPS does not intercept a certain percentage of natural lightning strokes. For reason of simplification IEC 62305-1 [1] fixes a set of minimum values of lightning parameters for each LPL. Of course, the interception efficiency is only linked to the air-terminations of a LPS.

The superposition of both efficiencies according to IEC 62305-1 [1] results in the values of the damage probabilities P_B for a LPS to reduce physical damages, which are given in IEC 62305-2 [4] (see Table IV). These values are essentially important for a complete risk analysis for structures.

TABLE IV. CORRELATION OF THE EFFICIENCIES OF A LPS AND THE DAMAGE PROBABILITIES IN THE STANDARD SERIES IEC 62305.

Lightning protection level (LPL) [1] and class of lightning protection system (LPS) [2]	**IV**	**III**	**II**	**I**
Sizing efficiency [1]	0,97	0,97	0,98	0,99
Interception efficiency [1]	0,84	0,91	0,97	0,99
Summarized (Total) efficiency	0,80	0,90	0,95	0,98
Damage probability P_B [4]	0,20	0,10	0,05	0,02

IV. REAL INTERCEPTION EFFICIENCIES USING THE DYNAMIC ELECTRO-GEOMETRICAL MODEL

The 15 cases described in Table III are investigated using the dynamic electro-geometrical model. Table V shows the interception efficiencies W_2 for the 15 cases, for a better comparison in a similar structure like Table III. The values are the sum for all existing air-termination rods, i.e. the percentages missing to 100% are the interception failures, which still strike the roof between the rods.

Fig. 8 – Fig. 11 show the results for four examples graphically, every figure representing one class of the LPS and one distance *d* of the air-termination rods. The figures demonstrate clearly the different interception efficiencies of rods at the roof's corner, the roof's edge, or the roof's centre.

TABLE V. INTERCEPTION EFFICIENCIES W_2 [IN %] ACCORDING TO THE DYNAMIC ELECTRO-GEOMETRICAL MODEL DEPENDENT ON THE CLASS OF THE LPS AND THE DISTANCE *D* OF THE AIR-TERMINATION RODS.

LPS class	**Distance of air-termination rods *d* [m]**			
	5	10	20	40
I	99,97	99,97	99,96	-
II	99,92	99,92	99,93	99,74
III	99,83	99,84	99,81	99,79
IV	99,53	99,56	99,64	99,65

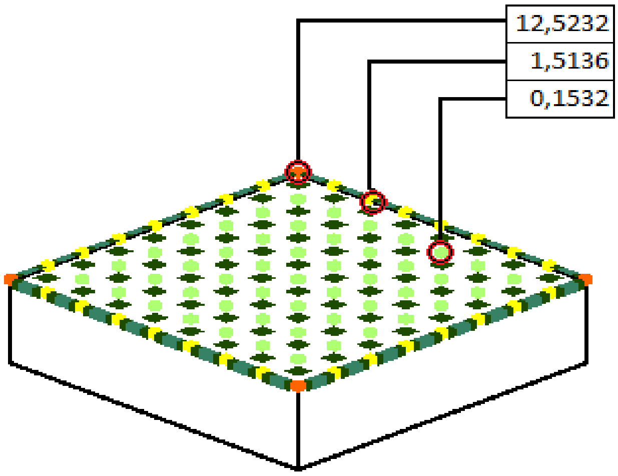

Figure 8. Interception efficiencies [in %] for LPS class I, distance of the air-termination rods *d* = 5m, height *h* = 30cm – 99,97% of all lightning strokes appear to the 81 rods.

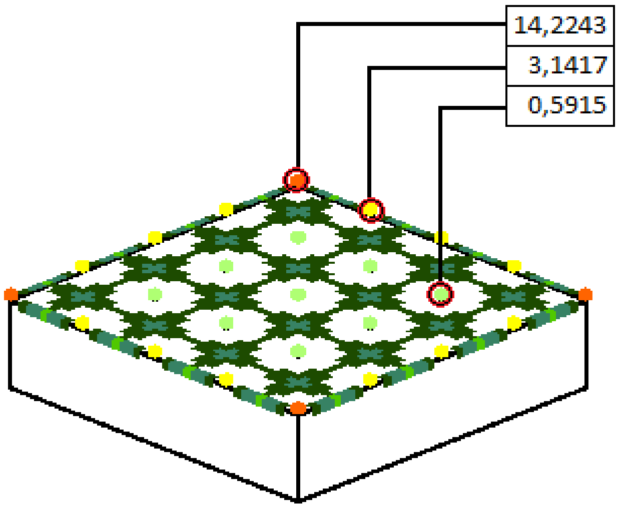

Figure 9. Interception efficiencies [in %] for LPS class II, distance of the air-termination rods *d* = 10m, height *h* = 90cm – 99,92% of all lightning strokes appear to the 25 rods.

It can be assessed, that the real interception efficiencies according to Table V are much higher than the values given by the standard series IEC 62305 [1, 4]. To show this once more and in a more simplified mode, the predicted interception failures for air-termination rods (1-W_1) according to Tables III and IV (IEC 62305) are compared with the real interception failures (1-W_2) according to Table V (dynamic electro-geometrical model). The relation F = (1-W_1)/(1-W_2) given in Table VI explains for the air-termination rods planned and installed according to IEC 62305-3 [2], how much more “effective” they are, than assumed by the standard series itself. For this comparison, however, one must take into account, that the values for F are dependent on the geometry of the structure (length, width, height, roof pitch, roof systems, etc.). Hence, the values of Table VI are valid only for the exemplary roof, but not universally for the individual classes of a LPS.

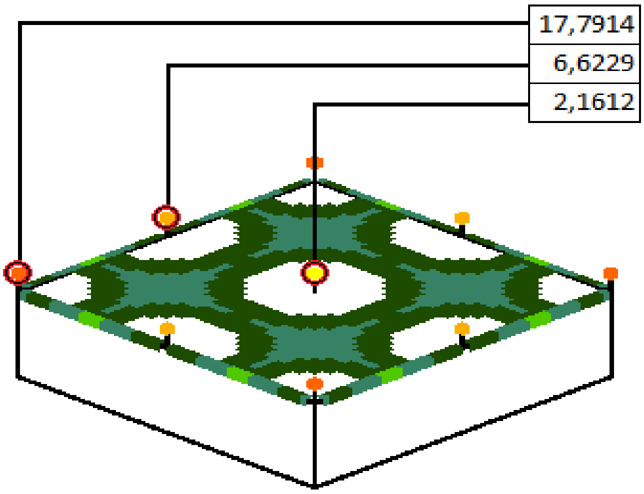

Figure 10. Interception efficiencies [in %] for LPS class III, distance of the air-termination rods d = 20m, height h = 2,3m – 99,81% of all lightning strokes appear to the nine rods.

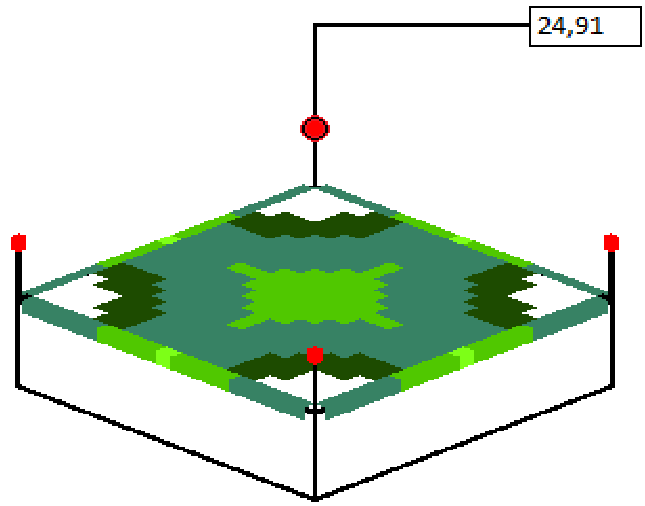

Figure 11. Interception efficiencies [in %] for LPS class IV, distance of the air-termination rods d = 40m, height h = 7,1m – 99,65% of all lightning strokes appear to the four rods.

TABLE VI. RELATION OF THE INTERCEPTION FAILURES F = (1-W_1)/(1-W_2) DEPENDENT ON THE CLASS OF THE LPS AND THE DISTANCE D OF THE AIR-TERMINATION RODS.

LPS class	**Distance of air-termination rods *d* [m]**			
	5	10	20	40
I	33	33	25	-
II	37	37	43	11
III	53	56	47	43
IV	34	36	44	45

V. CONCLUSION

The dynamic electro-geometrical model 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 strokes to different points on the surface of a structure. As supposed, the edges and corners of the structures are more exposed than flat surfaces.

It is shown that the interception efficiencies of air-termination rods, planned and installed according to the classical rolling-sphere method [3] are much higher, than predicted in the standard series IEC 62305 itself. Reason for that is the conservative approach of the rolling-sphere method, giving the LPS planner all possible points-of-strike, without an information about the striking probability. On the other hand this indicates that planning air-termination rods with the rolling-sphere method is on the “safe side”. However, sometimes and for some special cases of LPS it may be useful, to know the real interception efficiencies of air-termination rods, and then to perform a more detailed risk analysis [4]. The dynamic electro-geometrical model may help to document the improvement of the damage probabilities P_B in such cases.

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