Planning of Air-Termination Systems with the Dynamic Electro-Geometrical Model – Possible Practical Applications

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Abstract

Interception efficiency (IE) is the most important parameter to show the effectiveness of air-termination systems. The dynamic electro-geometrical model (DEGM), a numerical method, is capable of calculating such IE. This model is purely based on international accepted models, parameters, deviations and dependencies, which are also comprised in the IEC 62305. So far it has been used to calculate the IE for rod-type air-terminations.

This paper discusses possible applications using the DEGM. Based on an example two methods are shown and discussed: (1) For a conservative approach a comparison analysis is conducted: firstly, for an air-termination rod arrangement which is planned purely on the basis of IEC 62305-3 a detailed analysis with the DEGM gives an IE value (which usually is much better than expected from IEC 62305-1). This value for the IE is then secondly used for an "optimized" air-termination system based on the DEGM. This second version of the "optimized" air-termination system does not fulfill all planning procedures of IEC 62305-3. However, it leads to the same IE. (2) An even more progressive method uses simply the IE values given in IEC 62305-1 and tries to fulfill these values with a planned air-termination rod arrangement.

Keywords: interception efficiency; rolling-sphere; dynamic electro-geometrical model

1. Introduction

Planning of air-termination systems for structures is possible based on three methods given in the international standard for lightning protection IEC 62305-3 [1]:

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

The rolling-sphere method is the basic planning procedure. This method has been well-known for many years and has impressively shown its quality in a large number of standards for lightning protection. It is based on the electro-geometrical model, which strongly considers the physics of natural lightning [2].

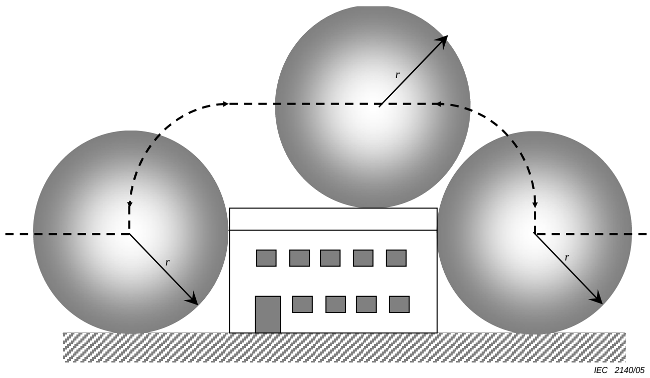

Fig. 1 Structure to be protected by rolling-spheres (radius r) – side view [1].

For the different requirements of lightning protection systems (LPS) four lightning protection levels (LPL) are defined which accumulate in four classes of LPS (I – II – III – IV) [1, 3]. They differ, regarding the rolling-sphere method, in the radii of rolling-spheres, which are fixed between 20 m and 60 m.

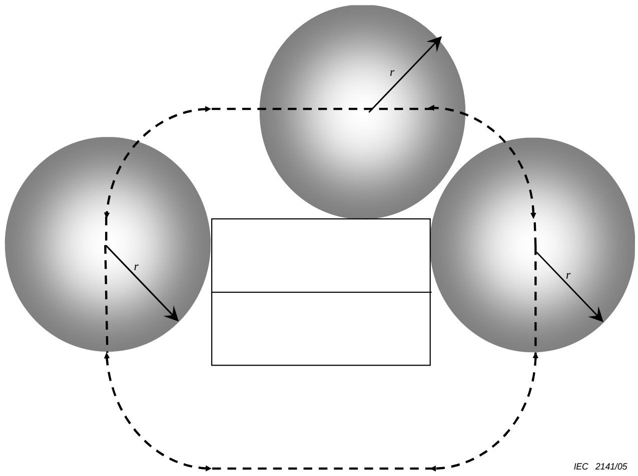

Fig. 2 Structure to be protected by rolling-spheres (radius r) – plan view [1].

With the fixed rolling-sphere radii different smallest current 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-termination system planned according to [1]. For risk analysis and risk management, calculations for damage probabilities depending on the different LPLs are defined in IEC 62305-2 [4]. The application of the rolling-sphere method points out possible point-of-strikes where air-terminations have to be placed. However, no information is contained on the probability of lightning flashes at these individual points. As an example a rectangular building with a saddle roof is considered (Fig. 1 and Fig. 2). It is obvious that the probability of flashes 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 therefore they have to be protected by an air-termination system as well. Hence, the "classical" rolling-sphere method does not provide a value of interception efficiency at the different point-of-strikes.

The so-called dynamic electro-geometrical model (DEGM) overcomes this issue. With this model a detailed calculation of striking probabilities at every point of an investigated structure is achieved and an evaluation for the interception efficiencies (IE) of all air-termination rods is possible [5, 6, 7]. The model uses the basic idea of the so-called collection surface method (CSM) developed by HARTONO and ROBIAH [8]. However, the CSM still uses fixed rolling-sphere radii, and overall does not consider the probability distributions of the lightning current peak values.

The aim of this investigation is to present two study cases of practical applications of the DEGM based on one example:

- The first one starts with an air-termination rod arrangement purely based on the concepts and methods given in IEC 62305-3 [1], i.e. standardized "rolling-sphere" method. For this arrangement the IE value is calculated with the DEGM. This IE value then serves as the base for an "optimized" air-termination arrangement. "Optimized" means that the number of rods may be reduced, and rods may be avoided at locations, where they are difficult to be installed or where the down-conductor connection is complicated. The removal of rods with very low IE may result in an increase of IE for the remaining rods. The overall value of the "optimized" air-termination system's IE must not be lower than the IE for the basic arrangement of the air-termination rod arrangement – conservative approach.
- The second one uses purely the IE value given in IEC 62305-1 [3] and simply tries to reach this value with an air-termination rod arrangement – progressive approach.

2. Dynamic electro-geometrical model

2.1 Probability distributions for lightning current peak values

Probability distributions for lightning current peak values are very well investigated. The actually so-called "CIGRE data" is the basis for most international standards on lightning protection, e.g. the IEC 62305 standard series. IEC 62305-1, Annex A [3] 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 this investigation the negative and the positive first strokes have to be considered. The parameters for the negative and positive first strokes are given in TABLE I and TABLE II according to (1). Finally, the individual distributions for negative and positive first strokes are combined, using the ratio of 90 % / 10 % according to [3].

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

2.2 Electro-geometrical model

Based on the electro-geometrical model a certain length for the striking distance, and with that the rolling-sphere radius *r*, can be linked to each lightning current peak value *I*. Enormous research work on this subject was performed. Nowadays the following description is given, also used in the international lightning protection standard series IEC 62305 [3]:

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

Inserting (2) in (1), by maintaining the characteristics of the density function, transforms the distributions for the lightning current peak values into distributions for the length of the striking distances, corresponding to the rolling-sphere radii *r*.

2.3 Numerical procedures

The entire surface of the structure to be protected including any air-termination system (e.g. rods) has to be discretized aerially, as well as the ground surrounding the structure (surface points – SuP).

The space outside the structure (above and besides) is discretized spatially (space points – SpP).

Using simple geometrical relations or equations, respectively for each space point the closest surface point can be found. The distance between space point and surface point is the striking distance and with that the rolling-sphere radius. For this radius (or the relevant radius interval as a result of the spatial discretization) according to (2), an interval of the lightning current peak value can be linked. With that, finally a probability value for a lightning flash from that space point to the surface point considered can be given. The steps mentioned above are generally conducted for all space points.

One surface point can be the closest to different space points (with different radii). Therefore, for each surface point all probability values which are calculated for it must be added. The sum of those is the final probability that lightning will strike there.

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

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 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 remarkably influence the starting process of the connecting leader, at least for flat objects on the ground.

An analytical approach in order to calculate the interception probability and the number of strikes into simple structures, to be expected as a result of a given ground flash density has been presented by HANNIG et.al. in [7]. The methodology is based as well on the approach of a dynamic electro-geometrical model (DEGM) and complies with the parameters and requirements expressed in the standard series IEC 62305. The analytical approach calculates cumulative weighted interception areas using enveloping surfaces. For this purpose, a formula has been derived, which solves the mathematical integration easily by inserting polynomial coefficients. The values were compared to published real lightning measurements and numerical simulations. Moreover, the absolute values of the calculated interception volumes can be related to the ground flash density and give reasonable answers to the question, how often lightning might strike a certain area of a structure. The results are very useful to verify different simulation methodologies and their accuracies, when dealing with the DEGM.

Different simulations have been verified with that analytical solutions and can be adjusted with different degrees of discretization [9].

3. Study case

The study case consists of a large depot, where on the flat roofs a PV system is planned to be installed. This is to be taken into account when planning and installing the air-termination system. Fig. 3 shows the depot including the PV modules. The main part of the building (120 m x 80 m) has got a height of 10 m, the smaller part at the right side (25 m x 80 m) is 20 m in height, both values include already the heights of the PV modules.

The LPS and especially the air-termination system shall be planned and installed according to class III and on the base of IEC 62305-3 [1]. This leads to a “rolling-sphere” radius of 45 m.

An LPS may fail in two different directions:

- The sizing efficiency (SE) 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 [3] for each LPL.
- With the interception efficiency (IE) it is intended to demonstrate that an LPS does not intercept a certain percentage of natural lightning strokes. For reason of simplification IEC 62305-1 [3] fixes a set of minimum values of lightning parameters for each LPL (TABLE III). Of course, the IE is only linked to the air-terminations of an LPS.

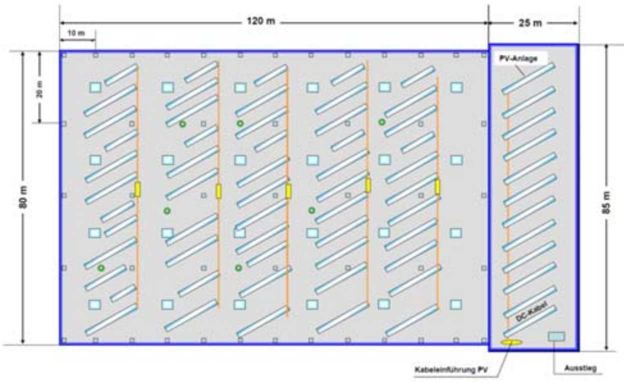

Fig. 3 Study case - Depot with PV modules on the roof – Basic arrangement and dimensions.

The superposition of both efficiencies according to IEC 62305-1 [3] results in the values of the damage probabilities P_B for an LPS to reduce physical damage, which is given in IEC 62305-2 [4] (see also TABLE III). These values are essentially important for a complete risk analysis for structures.

TABLE III
Correlation of maximum and minimum lightning peak current with the efficiencies of an LPS and the damage probabilities in the standard series IEC 62305.

Lightning protection level [3] and class of LPS [1]	IV	III	II	I
Max. peak current / kA [3]	100	100	150	200
Min. peak current / kA [3]	16	10	5	3
Sizing efficiency [3]	0.97	0.97	0.98	0.99
Interception efficiency [3]	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

With an LPS class III lightning current amplitudes down to 10 kA are considered, covering 91 % of all lightning discharges [3]. Therefore, we may assume that with this air-termination system at least 91 % of all lightning strikes are intercepted, or the interception failure is at most 9 %. For this investigation it is assumed, that the depot is standing alone, i.e. the influence of neighboring structures is neglected. This is a worst case assumption for the investigated complex.

The IE considers only the fact of a direct strike to the air-termination system. It does not consider the possible transient voltages induced into the structure’s equipment by the lightning current flow in the LPS.

4. Conservative approach

4.1 Planning according to IEC 62305-3

The conservative approach starts with an air-termination system which is fully based on the standardized rules and methods of IEC 62305-3 [1]. Fig. 4 shows such a solution with in total 40 air-termination rods:

- 30 air-termination rods with a height of 2 m protect the lower main part of the depot (120 m x 80 m). The rods are installed in distances of 20 m x 20 m (diagonal distance 28 m);
- 10 air-termination rods with a height of 3 m protect the taller part of the depot (25 m x 80 m). The rods are installed in distances of 25 m x 20 m (diagonal distance 32 m). The rods on the taller part of the depot have to be a little higher because of the increased diagonal distance.

The rods are planned with the rolling-sphere method. For an LPS class III a radius of 45 m has to be used. The arrangement shown in Fig. 4 prevents a contact of such a sphere with the roof or the PV modules installed there. This case is named base case.

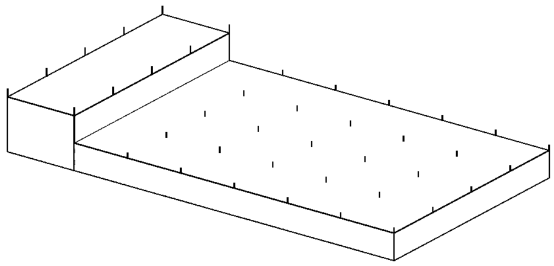

Fig. 4 Study case – Arrangement of air-termination rods planned according to IEC 62305-3 [1], LPS class III (rolling sphere method, radius 45 m).

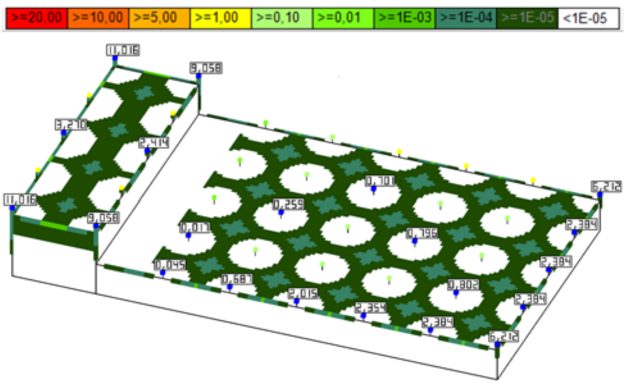

Fig. 5 Study case – Air-termination system according to IEC 62305-3, LPS class III (base case) - Detailed calculation of the IE with the DEGM (values give the percentage of strikes to an individual rod compared to all strikes to the structure).

A detailed calculation with the DEGM shows the IE of the individual rods (Fig. 5); the color gives an indication of the percentages. The following results arise from this calculation:

- in total 99.5% of all strikes go to the 40 rods;
- only 0.5% strike the PV modules or the roof, especially at the roof edges between rods;
- the rods at the corners are the most effective of the structure, especially at the depot's taller part (IE value 11.02%);
- the rods at the roof edges are also still comparatively effective with IE values between 3.27% and 0.69% (only the rods on the lower main part closest to the taller part show smaller IE values);
- the rods in the center of the depot's lower main part show IE between 0.80% and 0.017% only.

It is somewhat surprising that the overall IE of the 40 rods is **99.5%**, and with that the interception failure is 0.5% only. This is much better than the expected values based on IEC 62305-1 [3], which according to TABLE III fixes an IE of 91% only, allowing an interception failure of approx. 9%. However, this effect is well known for rods. For a rod arrangement to fail, a comparatively weak lightning flash (peak current < 10 kA for LPS III) must move downward in the middle between the rods. If such a flash moves downward directly or approx. directly above one rod, it will still strike this rod, and therefore it will not lead to an interception failure.

4.2 "Optimized" air-termination arrangements

Investigating the air-termination rod system of Fig. 5 in detail, it is worth mentioning that the most complicated rods are the ones in the roof center of the lower main part of the depot. Rods installed at the corners or edges of such a structure can be interconnected and connected to the down-conductor system easily; usually there is no separation distance problem to roof installations. However, considering the PV modules on the flat roof, it is obvious, that the down-conductors connected to air-terminations installed here in the center usually lead to separation distance problems. Of course, such problems can be solved. But this leads to the necessity of special arrangements (e.g. isolated LPS) being more expensive.

Therefore, if air-terminations can be avoided in the center of the roof, or even if their number can be reduced remarkably, this will lead to a reduction of costs of the entire LPS. The idea therefore is to "optimize" the air-termination system. The basic rule is:

Any "optimized" LPS is assumed to be "equivalent" if the overall IE is the same as the overall IE of the LPS based on the design rules of IEC 62305-3 [1], both cases calculated with the DEGM.

This conservative approach was firstly described by KERN et al [9] in 2016 for a simple arrangement of a tank. Here it is used again for a more complicated study case.

Fig. 6 shows a first example of such an "optimized" air-termination system:

- 10 rods with a height of 3 m again protect the taller part (25 m x 80 m). All these rods are at corners and edges, therefore simple to connect.
- 15 rods with a height of 2 m are again installed at the edges and corners of the lower part (120 m x 80 m), installed every 20 m.
- The 15 rods in the roof center (see Fig. 5) are replaced by only 2 rods, now having a height of 8 m. With that 13 rods are avoided, and, consequently, also a lot of connections to these rods

crossing PV installations and causing separation distance problems there.

The overall IE of this system is **99.1%**, i.e. the interception failure is 0.9%. This is close to the value of the standard case (Fig. 5) and with that can be assumed to be approx. equivalent. The IE values of the individual rods can also be investigated in Fig. 6. The deviations to the values given for the base case (Fig. 5) are very small. Only the values for the two tall rods in the center of the lower flat roof are remarkably higher; they collect more or less the IE values of the saved 15 rods of the base case.

It should be noted, that in the study case, due to the width of the depot (80 m), a complete avoidance of rods in the roof center is not possible for the conservative approach.

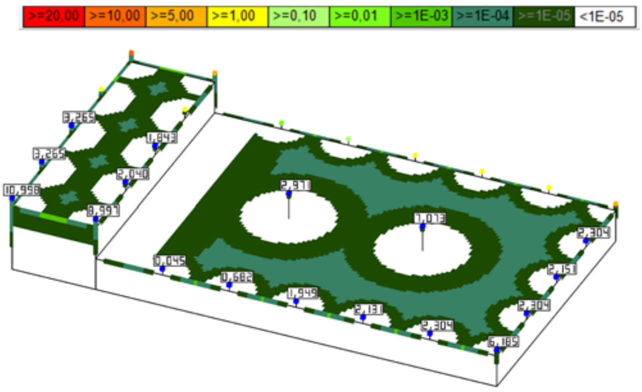

Fig. 6 Study case – Conservative approach: "optimized" air-termination system I: Height of the rods being 3 m (taller part), 2 m (edges and corners of lower part) and 8 m (roof center of lower part) - Detailed calculation of the IE with the DEGM.

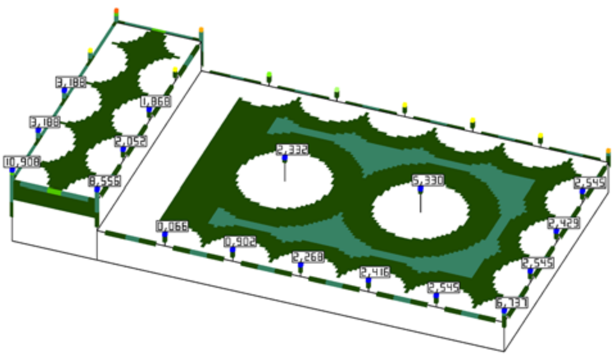

Fig. 7 Study case – Conservative approach: "optimized" air-termination system II: Height of the rods being 4 m (taller part and edges and corners of lower part) and 8 m (roof center of lower part) - Detailed calculation of the IE with the DEGM.

Fig. 7 shows a second example of an "optimized" air-termination system. The deviation from Fig. 6 is only that all the 25 rods at the roofs corners and edges have a height of 4 m instead of 2 m and 3 m, resp. The rods in the flat part's center are again 8 m high. The overall IE is now **99.6%** and with that still slightly better than in the base case.

It must be noted that small locations exist on protected structures with an air-termination system planned with the DEGM using the conservative approach, where a low probability of lightning strike to the structure is given with slightly higher peak values than for the selected class of LPS. In the study case this means that there are small locations with possible strikes with peak values > 10 kA.

It is obvious, that a various number of possible air-termination systems exists, which may fulfill the basic rule for the conservative approach mentioned above. It is the task of the LPS planner to find a suitable and economically good solution.

5. Progressive approach

Based on the fundamental values of the standard series IEC 62305 [1, 3, 4] given in TABLE III, a further more progressive approach may be also possible. Here, simply the IE values which are the base for the damage probability calculations are considered as the necessary values for a LPS to be planned and installed. Therefore, it is not necessary to plan an air-termination system fully based on the standardized rules and methods of IEC 62305-3 [1]. The necessary IE directly follows from the class of the LPS and is given by TABLE III.

Considering the study case, an LPS class III is to be planned and installed. This implies an IE value of 91%. Fig. 8 gives a first example for a possible air-termination system:

- 6 rods at edges and corners of the taller part with a height of 3 m with a spacing of 40 m;
- 7 rods at the edges and corners of the lower part with a height of 2 m with a spacing of 40 m.

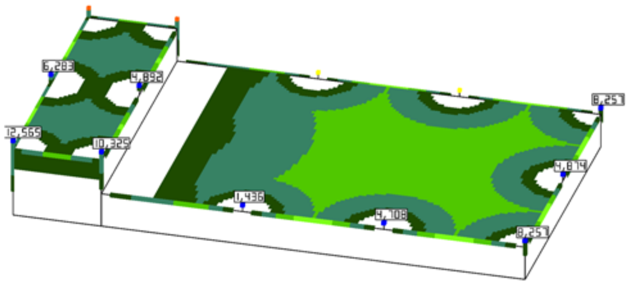

Fig. 8 Study case – Progressive approach I: Height of the rods being 3 m (taller part) and 2 m (lower part) with a spacing of 40 m installed at edges and corners only (total number of rods 13) - Detailed calculation of the IE with the DEGM.

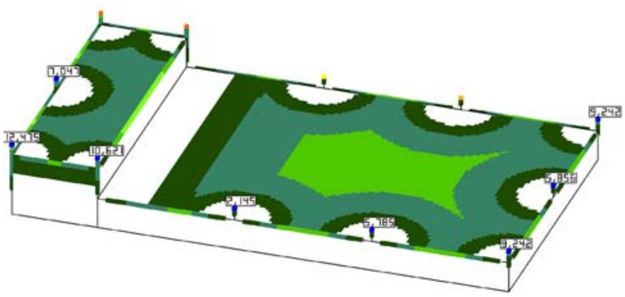

Fig. 9 Study case – Progressive approach II: Height of the rods being 4 m (taller part and lower part) with a spacing of 40 m installed at edges and corners only (total number of rods 12) - Detailed calculation of the IE with the DEGM.

This arrangement is derived from the base case, using entirely 13 rods. The spacing of the base case (20 m) is doubled, and all rods in the center of the lower part's roof are avoided. The overall IE is **90.7%**, and with that a little lower than necessary to fulfill the requirement of 91%. However, this case shows the possibility of significantly reducing the number of rods by keeping the rods heights.

Fig. 9 demonstrates a second example for an air-termination system using the progressive approach. Here all rods have a height of 4 m and they are installed at exactly the same locations as in Fig. 8, i.e. with a spacing of 40 m. Only the rod at the inner edge of the taller part in direction to the lower part is removed. The overall IE here is 93.5%, and with that clearly higher than necessary according to TABLE III for a LPS class III.

It must be noted again that areas exist on protected structures with an air-termination system planned with the DEGM using the progressive approach, where a certain probability of lightning strike to the structure is given with slightly higher peak values than for the selected class of LPS. In the given study case this means that there are areas with possible strikes with peak values > 10 kA.

Again, it is obvious that also for the progressive approach a large variety of air-termination systems may be possible. The planner could investigate and find a solution being a good compromise between the structure's characteristics and the economic benefit.

6. Conclusions

The dynamic electro-geometrical method (DEGM) was applied to large extended structures for determining the interception efficiency (IE) at locations on the structures, on used air-termination rods and for air-termination systems as a whole.

The study shows that air-termination systems planned by the standardized rolling-sphere method [1] own a much higher IE than previously thought, especially when using air-termination rods. Reason for such a high IE is found in the fact that very conservative minimum values of the IE are given in the standards [3, 4].

In particular, for structures in which planning of the air-termination system based on the standard does not lead to the desired protection goal, with the DEGM reserves can be exploited. Thereby air-termination systems can be achieved with an IE according to the class of LPS and an equal level of protection. This is now possible in two approaches:

- If an LPS is designed twice, once by planning the LPS exactly following the design rules given in IEC 62305-3 [1] (rolling-sphere radii, protection angle, etc.) and secondly by planning the LPS without restrictions using the available protection means, the evaluation of equivalence could be justified by calculating the overall IE for both cases using the DEGM. An LPS is assumed to be "equivalent" if the overall IE of the LPS based on the current design rules of IEC 62305-3 [1] is the same as the overall IE of the LPS planned with the DEGM. This approach is named "conservative" and could be possibly used without major restrictions.
- A second approach is named "progressive", and for that only the fundamental IE values given in the standards [3, 4] and used for the damage probability values in risk calculations are used. This approach usually leads to a remarkably reduced number of air-termination rods, and with that to a clear reduction of the costs for an LPS: only the most effective rods stay and the others may be removed. However, it must be stated that this approach uses only the IE values. It does not use the peak current limit values, which are also given in IEC 62305-1 [3]. Insofar, this approach goes much further than the conservative one. This should be clearly remarked as a necessary restriction of this approach.

Both approaches help to reduce the effort for air-termination systems. This is shown in this paper for a large extended, but still geometrically simple structure. It may be even more meaningful in case of geometrically more complex structures, and in case of structures considering also their neighborhood, where it is not so simple to identify the rods with the lowest efficiencies which may be removed or replaced. In such cases, the DEGM may serve as a modern and effective planning tool.

Finally, it should be critically noted that locations or areas exist on protected structures with an air-termination system planned by the DEGM where the required total IE according to the selected LPS class is just reached and where a low probability of lightning strike to the structure is given with slightly higher peak values than for the selected class of LPS. This effect is even more valid for the progressive approach than for the conservative.

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