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Detailed Calculation of Interception Efficiencies for Air-Termination Systems using the Dynamic Electro-Geometrical Model – 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 interception efficiencies. 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 interception efficiencies for rod-type air-terminations.**

This paper discusses applications using the DEGM. A detailed analysis shows that for a rod-based air-termination system the IE is much better than expected. This leads to the idea of a comparison analysis between an air-termination system purely planned according to the standardized "rolling-sphere" method and an "optimized" air-termination system based on the DEGM.

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

I. 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].

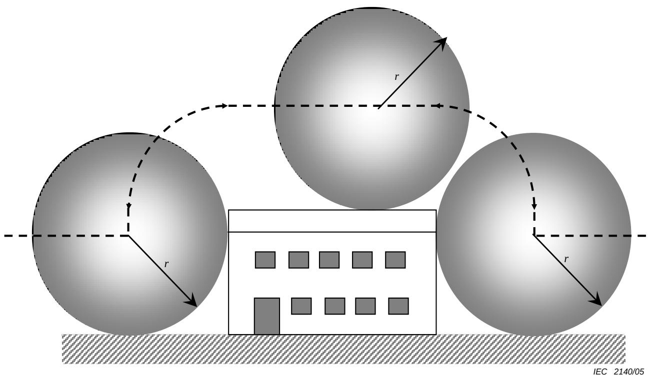

Figure 1. Structure to be protected by rolling-spheres (radius r) – side view [1]

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.

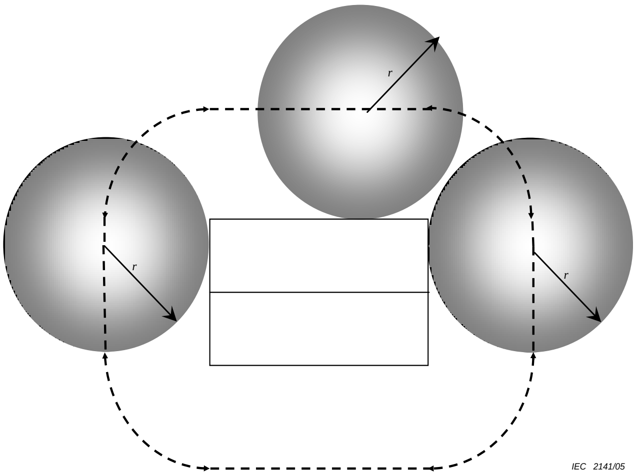

Figure 2. Structure to be protected by rolling-spheres (radius r) – plan view [1]

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 as examples of practical applications of the DEGM. The first one shows the very good IE of air-termination systems based on rods. The second one discusses the removal of a single rod from an air-termination system purely planned according to the standardized "rolling-sphere" method in [1]. The removal of rods with very low IE may result in an increase of IE for the remaining rods. Furthermore, the overall value of the air-termination system's IE is not significantly reduced.

II. DYNAMIC ELECTRO-GEOMETRICAL MODEL

A. 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, 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:

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

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 Tab. I and Tab. 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

B. 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]:

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

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*.

C. Numerical procedures

The entire surface of the structure to be protected including any air-termination system (e.g. rods) has to be discretized areally, 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.

III. STUDY CASE 1 – INDUSTRIAL COMPLEX

This study case consists of an industrial complex with three production halls (with logistic areas) and two production towers (Fig. 3):

- Hall A (left): 73 m (L) x 43 m (W) x 21 m (H);
- Hall B (center): 91 m (L) x 58 m (W) x 26 m (H);
- Hall C (right): 120 m (L) x 58 m (W) x 26 m (H);
- Tower A (left): 12 m (L) x 24 m (W) x 25 m (H);
- Tower C (right): 12 m (L) x 15 m (W) x 35 m (H).

The roofs of all structures including some roof systems shall be protected against direct lightning strikes by air-termination rods.

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. Using this planning tool leads to 82 air-termination rods with heights between 2 m and 6 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. Of course, the IE is only linked to the air-terminations of an LPS.

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 Tab. III). These values are essentially important for a complete risk analysis for structures.

TABLE III. CORRELATION OF THE EFFICIENCIES OF AN LPS AND THE DAMAGE PROBABILITIES IN THE STANDARD SERIES IEC 62305.

Lightning protection level (LPL) [3] and class of LPS [1]	**IV**	**III**	**II**	**I**
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 %. It is assumed that the industrial complex is a standing alone one, i.e. the influence of neighboring structures is neglected. This is a worst case assumption for the investigated complex.

The result of the IE calculated with the DEGM is presented in Fig. 3. It shows the values graphically for all roof areas and gives the numerical values for some interesting air-termination rods, especially those with higher values of the IE. Generally the results are:

- in all 82 air-termination rods 99.6 % of all lightning strikes occur
- only < 0.4 % of all strikes go to the (unprotected) roof areas

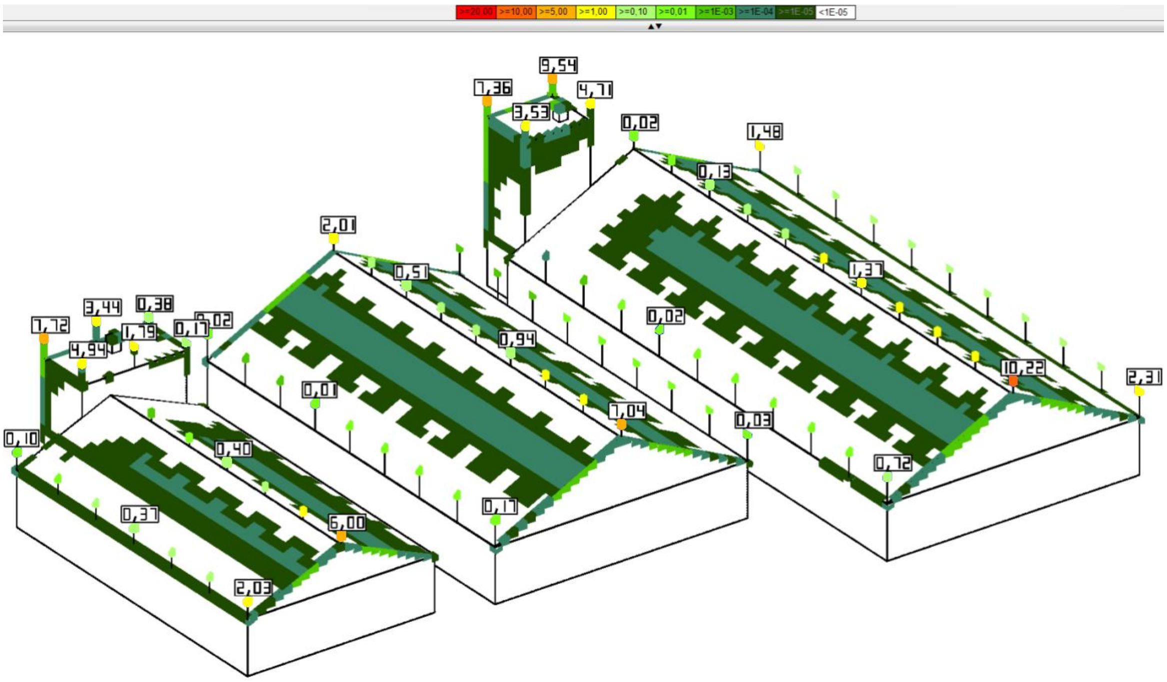

Figure 3. Industrial halls and auxiliary buildings with air-termination systems (82 rods) – graphical representation of the interception efficiencies and numerical values (in %) for selected rods.

If the five different structures of the industrial complex are investigated separately, one gets the values in Tab. IV.

TABLE IV. DETAILS OF THE INTERCEPTION EFFICIENCIES FOR STUDY CASE 1

Structure	Percentage of strikes to air-termination rods, related to all strikes in the industrial complex	Percentage of interception failures, related to all strikes in the industrial complex
Hall A	12.1%	0.05%
Hall B	15.2%	0.14%
Hall C	28.6%	0.15%
Tower A	18.5%	< 0.01%
Tower C	25.2%	< 0.01%
Sum	99.6%	< 0.4%

The air-termination rods intercept 99.6 % of all lightning strikes. The interception failure rate is less than 0.4 %. This is in a first approach approx. 20 times less than usually expected for LPS class III.

Going into detail (see Fig. 3), it is obvious that the air-termination rods show very different values for the IE:

- Some individual rods have got at the towers and at the gable corners of the halls have IE values of 5 % … 10 % (always related to all strikes in the industrial complex).
- The rods have got at the hall's gables usually have IE values between 0.5 % … 1 %.
- Many rods have got at the hall's eaves have IE values of only less than 0.1 %.

IV. STUDYCASE 2 – OIL AND GAS TANK

A second algorithm has been developed using the same formulas (1) and (2) but a completely different numerical approach. Its main benefit is the use of an irregular triangle mesh, which gives the opportunity of meshing very complex structures, also from CAD-tools. The whole methodology is described in [7]. To verify the validity of the numerical approach in general an analytical solution for 3 simple structures is also presented in [7]. When discretization is increased the numerical simulation is in very good agreement to the analytical solution.

A prerequisite for the second algorithm is that the building's structure to be considered is designed with the help of a 3D CAD program. After designing the building's structure, a 3D model is provided in a neutral data exchange format. With the help of a mesh program, the surface of the building's structure can be coated with an irregular mesh. The finer this discretization of the surface is the more exact is the calculation result. However, the calculation time increases along with the number of surface elements. In this case, a compromise must be found between the density of the discretization and the required calculation time. The results (probabilities of strike) are displayed in a logarithmic scaled false color plot. In this context, areas with a low IE are dark-colored. The brighter the color of the surface, the higher is the IE to the relevant area.

In this example, the DEGM is used to numerically examine the efficiency of a conventional LPS. Originally it is planned according to the conventional rolling-sphere method.

The object considered here, is a tank with a diameter of 60 m and an LPS which complies with LPS class II. Hence 18 air-termination rods were evenly distributed along the circumference of the tank. A particular challenge, when planning the LPS is the protection of the tank roof, which is designed as a floating roof. Due to the tank diameter of 60 m a rolling-sphere radius of 30 m according to the LPS class II, the rolling-sphere touches the roof surface of the tank in the center of the roof. Therefore, another air-termination rod was installed in the center of the tank roof. Fig. 4 shows the complete air-termination solution with the floating roof raised to its highest position.

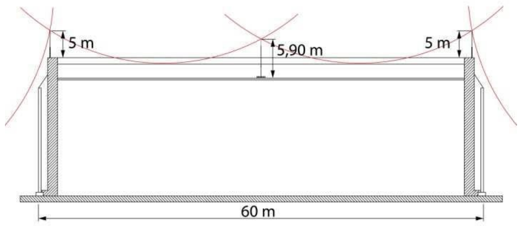

Figure 4. Protected volume of the air-termination system (floating roof raised to its highest position)

The air-termination rods are sufficiently dimensioned according to LPS class II. The examination of the LPS shown in Fig. 4 leads to the IE in the false color plot shown in Fig. 5.

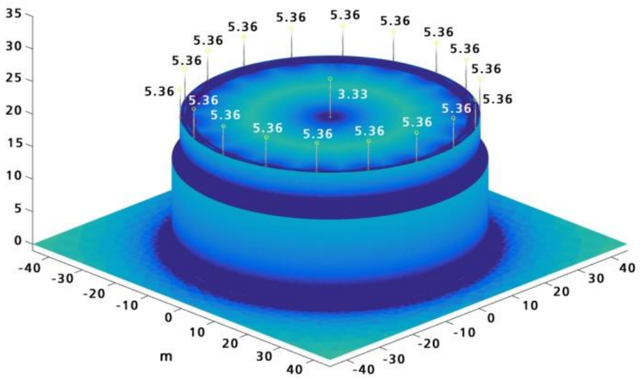

Figure 5. Graphical representation of the interception efficiencies and numerical values (in %) for the LPS in Fig. 4 (raised position)

The sum of the individual probabilities of each air-termination rod defines the overall IE to the air-termination system of the tank. The calculated overall IE of all air-termination rods and thus the interception efficiency of the LPS is 99.81 %. Consequently, the LPS meets the planning requirements for LPS class II (Tab. III) when the floating roof is raised to its highest position.

The height of the floating roof and thus the position of the air-termination rod in the center of the roof depend on the tank level. Therefore, the protected volume of the air-termination rods also has to be examined when the floating roof is lowered to its lowest position. As can be seen in Fig. 6, it can be proven by means of the conventional rolling-sphere method that the tank is also protected according to LPS class II when the floating roof is at its lowest position.

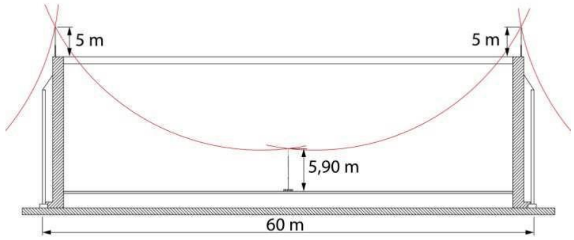

Figure 6. Protected volume of the air-termination system (floating roof lowered to its lowest position)

This solution was also examined with the help of the DEGM (Fig. 7). As assumed, there are slightly different IE in Fig. 5 and Fig. 7. Whereas in raised position each air-termination at the circumference shows an IE of 5.36 % and an overall IE of 99.8 % can be observed, in lowered position the IE per air-termination is 5.54 % and overall is 99.77 % respectively.

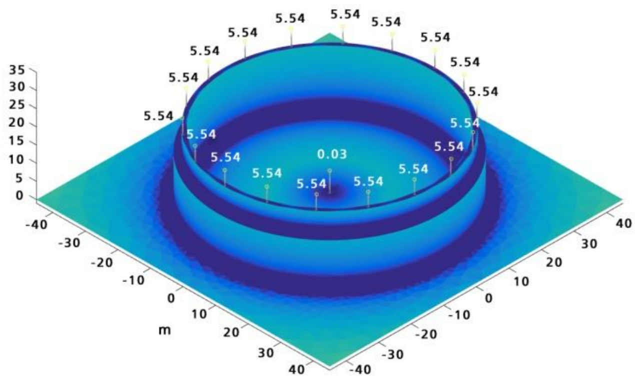

Figure 7. Graphical representation of the interception efficiencies and numerical values (in %) for the LPS in Fig. 6 (lowered position)

It is reasonable that the overall IE is slightly higher when the floating roof is raised than when it is lowered. In consequence the IE to the air-termination rods mounted along the circumference of the tank changes to lower values. This is due to the fact that when the roof is lowered the air-termination rod in the center of the roof no longer presents a point of strike for lightning strikes with large striking distances, namely large rolling-sphere radii, due to the resulting relatively low sag of the rolling-sphere into the tank.

Fig. 7 also shows that weak lightning may still strike the inside of the tank wall when the floating roof is lowered. According to the protected volume in Fig. 7, these lightning strikes are only lightning discharges with final striking distances of less than 30 m and low currents (< 5 kA) which occur relatively seldom and have got a low potential for damage.

V. OPTIMIZATION OF AIR-TERMINATIONS

The positioning of an air-termination rod in the middle of the floating roof of the tank only slightly increases the IE and the electrical connection to the earthing system can only be done by flexible cables. The DEGM was used to evaluate an LPS with an optimized air-termination system.

By calculating the total IE of different air-termination systems an optimized approach could be found. The evaluation criterion for the optimized air-termination system was defined as follows:

The 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.

The calculation results in Fig. 5 show that in raised position the air-termination rod in the middle of the floating roof takes over a certain share of the overall IE. If the optimized design approach aims to skip the air-termination rod in the middle of the floating roof of the tank the lowered overall IE must be "balanced" by a greater height or a bigger number of air-termination rods placed on the outer circle of the roof. With the variation of both parameters, the height and number of rods, an optimized LPS could be found. If the air-termination system of the LPS is formed by 18 rods with a height of 7 m the calculations using the DEGM for raised position an IE of 5.54 % per air-termination and an overall IE of 99.73 % can be observed, in lowered position the IE is 5.55 % and overall is 99.76 % respectively.

The results of the specific IE for the oil and gas tank with the roof in raised position are shown in Fig. 8.

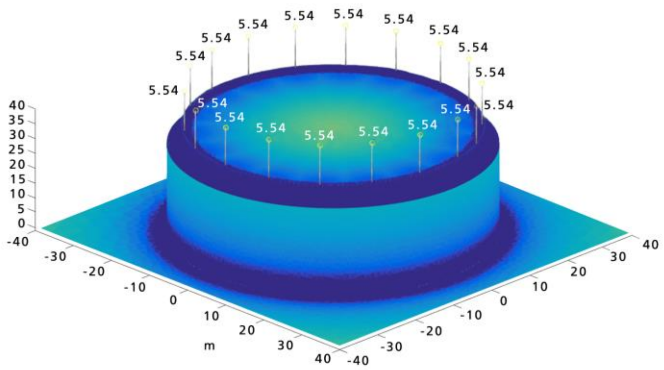

Figure 8. Graphical representation of the interception efficiencies and numerical values (in %) for an optimized LPS

VI. 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 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 minimum values of the IE are given in the standards [3, 4].

In particular, for structures in which planning of the air-termination system 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.

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.

It should be critically noted that small locations 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.

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