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CALCULATION OF INTERCEPTION EFFICIENCIES FOR MESH-TYPE AIR-TERMINATIONS ACCORDING TO IEC 62305-3 USING A DYNAMIC ELECTRO-GEOMETRICAL MODEL

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***Abstract* — Interception efficiency is the most important parameter to show the effectiveness of air-terminations. With the dynamic electro-geometrical model, a numerical method, it is possible to calculate such interception efficiencies. This model is based purely on internationally accepted models, parameters, and dependencies. So far it is used to calculate the interception efficiencies for rod-type air-terminations.**

An adaption of this model allows the calculation of interception efficiencies for mesh-type air-terminations. Up to now the effectiveness of this kind of air-terminations could only be shown on an "empirical base". This gap could be closed now using the results of this paper.

Keywords – interception efficiency; mesh-type air-termination; dynamic electro-geometrical model

I. INTRODUCTION

Planning of air-terminations 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 is well-known since 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].

For different requirements for lightning protection systems (LPS) four lightning protection levels (LPL) are defined, and based on that finally four classes of LPS (I – II – III- IV) [1, 3]. They differ regarding the rolling-sphere method in the rolling-sphere's radius, which is fixed between 20 m and 60 m.

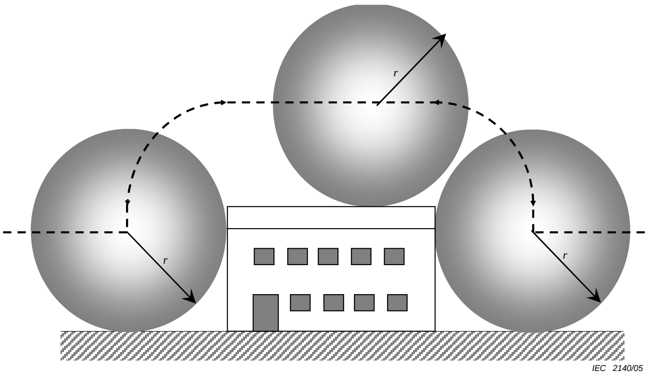

Figure 1. Structure to be protected with rolling spheres (radius *r*) – side view [1]

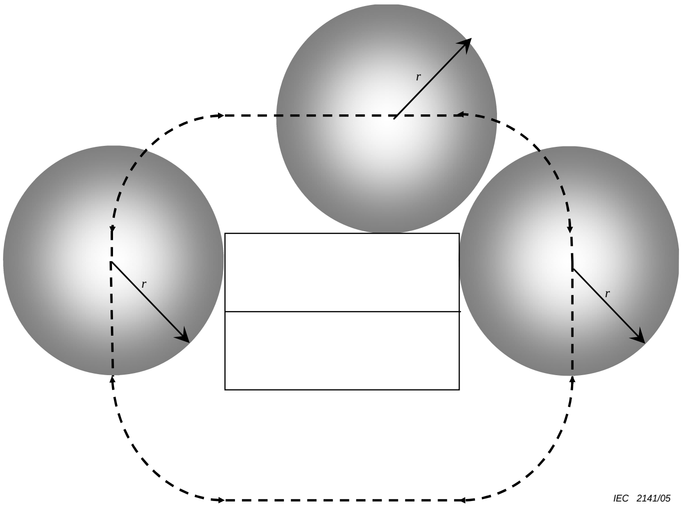

Figure 2. Structure to be protected with rolling spheres (radius *r*) – plan view [1]

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 [1]. For risk analysis and risk management calculations damage probabilities depending on the different LPL are defined in IEC 62305-2 [4]. It is a fact that planning with the rolling-sphere leads to possible point-of-strikes, where air-terminations have to be placed. However, no direct information is contained on the probability of lightning flashes at these individual different points. As an example a rectangular building with a flat roof is considered (Fig.1 & 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 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.

The so-called dynamic electro-geometrical model tries to solve this problem. With this model a detailed calculation of striking probabilities at different points of a structure and with that of interception efficiencies for air-termination rods is possible [5, 6]. The model uses the basic idea of the so-called collection surface method (CSM) developed by HARTONO and ROBIAH [7]. However, the CSM still uses fixed rolling-sphere radii, and with that does not consider the probability distributions of the lightning current peak values.

Using the basic idea of the dynamic electro-geometrical model in this paper the calculation of interception efficiencies for meshed conductors as air-terminations for flat roof areas is conducted. Up to now the effectiveness of such meshes could be shown only by empirical studies. However, discussions within international standardization committees (e.g. CENELEC TC81X) show that it is very difficult and sometimes even impossible to demonstrate the effectiveness of air-terminations only empirically without a validated and widely respected model.

The results given in this paper link the interception efficiencies of meshed conductors to the electro-geometrical model. For that the meshed conductors must be installed in a certain height above the volume which has to be protected. The calculated interception efficiencies depend on these heights. As a conclusion minimum heights of the meshed conductors can be given, so that the requirements for the different LPL are met.

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 actual so-called "CIGRE data" are the basis for international standards on lightning protection, the standard series IEC 62305. 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 first strokes described via (1) are given in Table 1, for the positive first strokes in Table 2. Finally the individual distributions for negative and positive short strokes are combined, using the ratio 90%/10% according to [3].

TABLE I. PARAMETERS OF THE NEGATIVE FIRST STROKE DISTRIBUTION

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

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, also used in the international lightning protection standard series IEC 62305 [3]:

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

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 [2]. 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 [3] 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%.

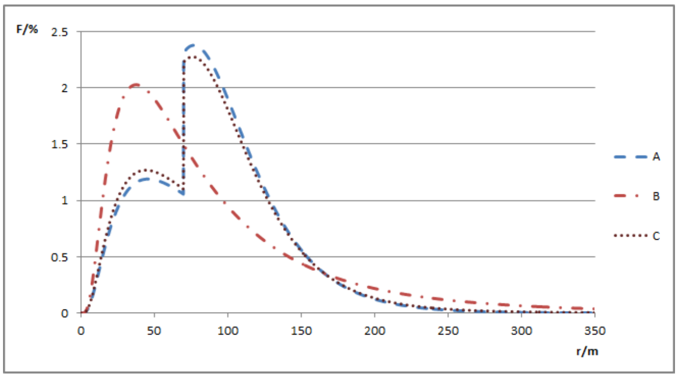

Figure 3. Density functions *F(r)* for the rolling sphere radius *r* based on the lightning current peak value descriptions given in [3]

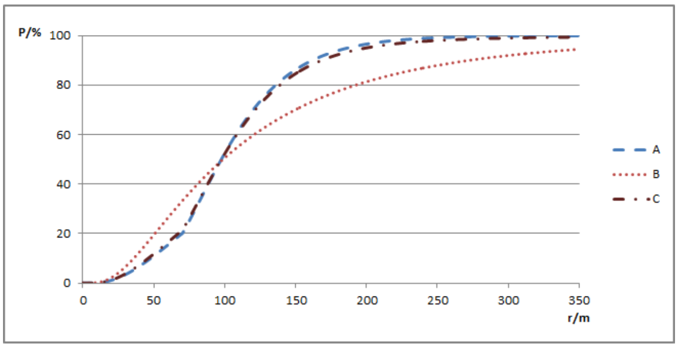

Figure 4. Cumulative frequency distribution function *P(r)* for radius *r* based on the lightning current peak value descriptions given in [3]

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 [3], and that it takes into account negative and positive first short strokes.

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 meters is usually sufficient. However, in special cases (e.g. heights of air-termination rods of only some 10 cm) a much finer discretization distance is necessary.

The space outside the structure (above and besides) is discretized spatially (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 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 generally are conducted 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 are 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 flash 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 flash 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 so far used rods as air-terminations [5, 6]. This is on the one hand due to the comparably high interception efficiencies of Franklin rods. On the other hand also the necessary discretization distances must lie only in the range of 0.5 m up to 2 m, because the rods are typically not smaller. However, in the case of meshed conductors the discretization distance must comply at least with the height of the meshes above the flat roof, i.e. it may be reduced down to 0.05 m. This leads to an extremely high number of discretized volume elements, and with that the algorithm of the dynamic electro-geometrical model has to be adjusted.

III. IMPLEMENTATION OF THE DYNAMIC ELECTRO-GEOMETRICAL MODEL FOR MESHED CONDUCTORS

A basic configuration of meshed conductors protecting a flat roof is shown in Fig. 5. A mesh according to IEC 62305-3 [1] is a quadratic arrangement of air-termination wires. Because of this symmetry the calculations for this investigation can be easily limited. Instead of simulating the entire roof in Fig. 5 it is sufficient to consider only one single mesh of the air-termination (Fig. 6). In this mesh only lightning flashes are possible, if the head of the downward leader is directly above the mesh, when the final jump starts. If the head of a downward leader is laterally shifted, the flash will occur in a neighbored mesh. If this neighbored mesh shows identical size and mesh width, the results for the investigated mesh can be transferred to the entire mesh arrangement. With that only the space directly above the investigated mesh has to be discretized.

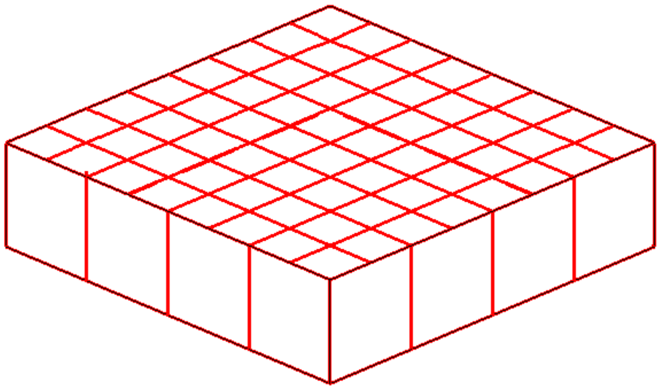

Figure 5. Air-termination system using meshed conductors for LPS class I on a structure 40 m x 40 m x 10 m

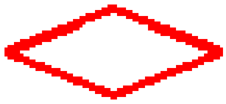

Figure 6. Investigated single mesh

The investigation is performed for the four different mesh sizes according to [1]. Mesh sizes, corresponding values for the rolling sphere radii, and the maximum allowed lightning peak currents, efficiencies and damage probabilities for the four different Lightning Protection Levels (LPL) [3, 4] and with that the four different classes of Lightning Protection System (LPS) [1] are given in Table III.

For the four basic mesh sizes the distance to the flat roof is varied. Though according to [1] there is no definition of a necessary height of the meshed conductors above the volume to be protected, it is obvious that a mesh being mounted directly on the roof surface will have almost no interception efficiency, if it is investigated using the electro-geometrical model. Therefore eight different heights between 5 cm and 50 cm are chosen. To apply the dynamic electro-geometrical model to the mesh structure, first the meshed conductors must be discretized. The discretization distance must be dependent on the height of the meshed conductors. For all different cases the constant discretization distance of 5 cm, according to the smallest mesh height chosen, is used. This facilitates the comparison of the final results.

As the next step the surface of the meshed conductors (surface points) can also be interpreted as the tips of small rods standing together very closely (Fig. 7). Again the value of 5 cm is used as the lateral distance of these small rods. Using this procedure the existing basic algorithm of the dynamic electro-geometrical model can be applied. Finally the surface area of the flat roof inside the mesh is discretized using the same distance value of 5 cm.

TABLE III. DATA FOR THE INVESTIGATED MESHES ACCORDING TO THE STANDARD SERIES IEC 62305 [1, 3, 4]

(LPS) [1] and LPL [3]	**I**	**II**	**III**	**IV**
Mesh width d in m [1]	5	10	15	20
Rolling-sphere radius r in m [1, 3]	20	30	45	60
Maximum allowed lightning peak current in kA [3]	3	5	10	16
Interception efficiency [3]	0.99	0.97	0.91	0.84
Sizing efficiency [3]	0.99	0.98	0.95	0.95
Summarized (Total) efficiency	0.98	0.95	0.90	0.80
Damage probability P_B [4]	0.02	0.05	0.10	0.20

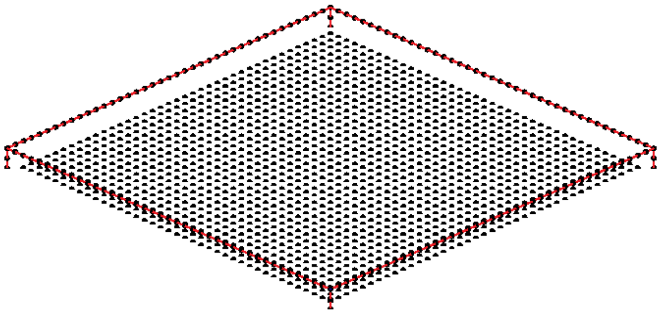

Figure 7. Discretized structure of the mesh and the flat roof inside

IV. RESULTS

A. *"Classic" rolling-sphere method*

For comparison the necessary height of the meshed conductors is calculated, if the "classic" rolling-sphere method according to IEC 62305-3 [1] is applied for the meshes. Using this consideration, and based on the data given in Table III, this height can be calculated, so that lightning strikes with peak currents exceeding the values fixed for the relevant LPL do not contact the flat roof's surface. Fig. 8 shows the area (side length k) for a given penetration p (= height of the meshed conductors), where a rolling-sphere with radius r still contacts the roof. For p_{min} there is no more contact of the rolling-sphere to the roof, i.e. $k = 0$ (see values in Table IV):

$$p_{\min} = r - \sqrt{r^2 - \left(\frac{d}{2}\right)^2} \tag{3}$$

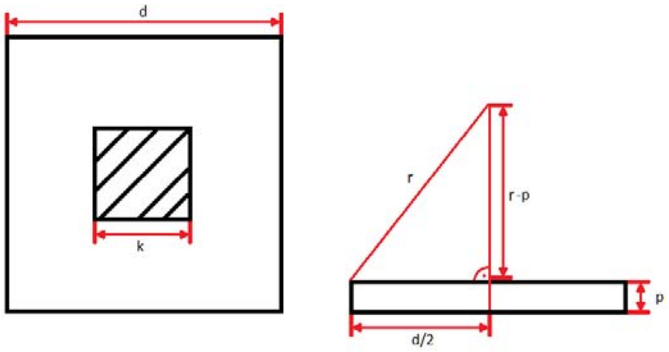

Figure 8. Geometric dependence of rolling sphere radius r, mesh width d, and penetration depth p

TABLE IV. MINIMUM PENETRATION DEPTH p_{min} BETWEEN THE MESH AND THE FLAT ROOF IF USING THE ELECTRO-GEOMETRICAL MODEL ACCORDING TO IEC 62305 [1]

Class of LPS [1]	**I**	**II**	**III**	**IV**
Mesh width *d* in m [1]	5	10	15	20
Rolling-sphere radius *r* in m [1, 3]	20	30	45	60
Minimum penetration depth p_{min} in cm	16	42	63	84

The results given in Table IV indicate that meshed conductors have to have a height above the flat roof of 16 cm (for LPS I, mesh width 5 m) up to 84 cm (for LPS IV, mesh width 20 m). While a value of 16 cm still seems to be possible to be realized, the values calculated for the other mesh sizes in the range of some tens of cm up to almost 1 m are clearly outside an easy achievable range for mesh-type air-terminations.

B. *Dynamic electro-geometrical model*

32 mesh configurations (four mesh sizes, eight heights above roof) are investigated using the dynamic electro-geometrical model. The resulting interception efficiencies are given in Table V; Fig. 9 illustrates these results. Another view of the results is given in Fig. 10 & Fig. 11 representing the remaining interception failures. Instead of the penetration depth *p* according to [1] the term height *h* above the flat roof is used to describe the necessary distance of the meshed conductors to the volume to be protected.

TABLE V. INTERCEPTION EFFICIENCIES OF THE INVESTIGATED MESHES [IN %] USING THE DYNAMIC ELECTRO-GEOMETRICAL MODEL

	Mesh width *d* in m			
Height above roof *h* in cm	**5**	**10**	**15**	**20**
5	99.11	85.97	69.36	57.85
10	99.86	95.87	83.65	71.60
15	99.96	98.29	90.89	80.17
20	99.99	99.09	94.69	85.89
25	99.99	99.47	96.69	89.84
35	99.99	99.79	98.40	94.50
45	99.99	99.90	99.08	96.76
50	99.99	99.93	99.29	97.43

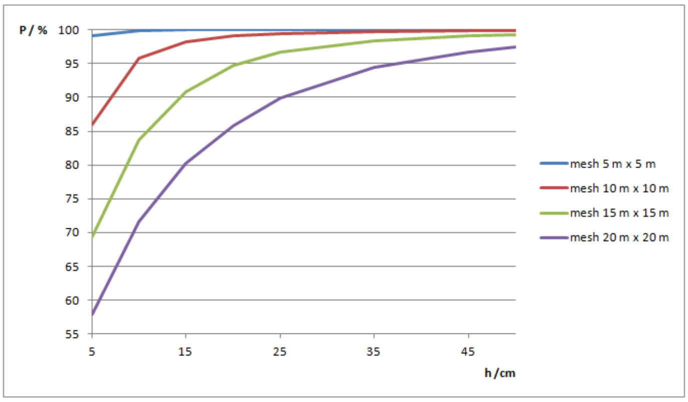

Figure 9. Interception efficiencies [in %] for the four mesh sizes dependent on the height *h* of the meshed conductors above the flat roof

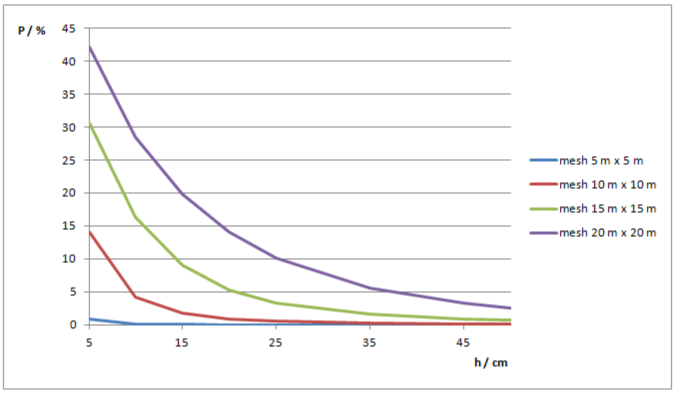

Figure 10. Interception failures [in %] for the four mesh sizes dependent on the height *h* of the meshed conductors above the flat roof

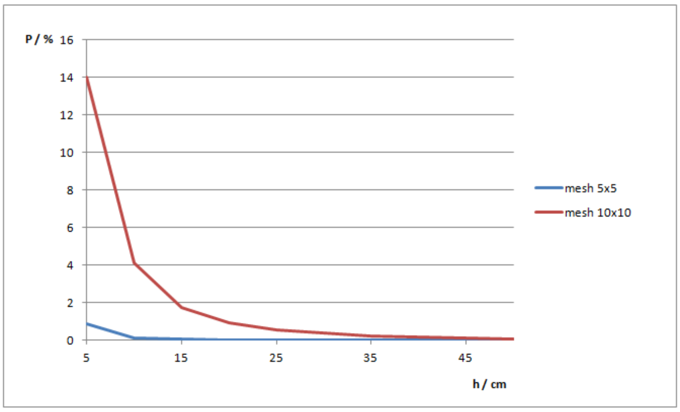

Figure 11. Interception failures [in %] dependent on the height *h* of the meshed conductors above the flat roof (detailed view for the mesh sizes of LPS class I and II)

Now the meshes can be qualified using the interception efficiency, and with that the acceptable remaining interception failure, as described in the standard series IEC 62305 for the different classes of LPS (Table III). LPS I requires an interception efficiency of 99%, i.e. an interception failure of 1% is accepted. Therefore a mesh with a width of 5 m x 5 m needs to be installed in a distance of approx. 5 cm above the roof. If this height is increased further the interception efficiency is improved only marginally.

A mesh 10 m x 10 m for LPS II has to have a height of more than 10 cm to ensure the necessary interception efficiency of 97%. In case of 15 cm distance to the roof a level of more than 98% interception efficiency is reached.

If a mesh 15 m x 15 m for LPS III is installed in a height of approx. 15 cm, the requirement for the interception efficiency of 91% is fulfilled. A distance of 20 cm above the roof leads to an increase to 95% interception efficiency.

Finally, for LPS IV and a mesh width of 20 m x 20 m the height above the roof must achieve about 20 cm to get the interception efficiency of 84%.

V. CONCLUSIONS

Generally we may conclude that with increasing mesh width also the distance (height) to the flat roof has to be increased to ensure a certain level of interception efficiency.

For the four mesh sizes according to IEC 62305-3 [1] heights h above the flat roof from 5 cm (LPS I) up to 20 cm (LPS IV) are necessary to reach the interception efficiencies given in IEC 62305-1 [3]. This is a result of numerical calculations using the dynamic electro-geometrical model. These height values are significantly lower than the values which we get using the principles of the „classic“ rolling-sphere method for the same approach [1].

The interception efficiencies given in this paper for the meshed conductors are a result of numerical calculations based on a model intensively reviewed over decades in a huge amount of scientific studies and accepted by the international scientific community: the electro-geometrical model. Therefore these results seem to be much more credible than results from empirical studies where the data base sometimes might be at least doubtful.

REFERENCES

[1] IEC 62305-3 Ed.2: 2010-12: Protection against lightning – Part 3: Physical damage to structures and life hazard.

[2] V. Cooray, and M. Beccera, “Attachment of lightning flashes to grounded structures”, Chapter 4 of Lightning Protection (V. Cooray editor), The Institution of Engineering and Technology, London, 2010.

[3] IEC 62305-1 Ed.2: 2010-12: Protection against lightning – Part 1: General principles.

[4] IEC 62305-2 Ed.2: 2010-12: Protection against lightning – Part 2: Risk management.

[5] A. Kern, C. Schelthoff, and M. Mathieu, “Probability of lightning strikes to air-terminations of structures using the electro-geometrical model theory and the statistics of lightning current parameters”, Proc. of 30th International Conference on Lightning Protection (ICLP), Cagliari (IT), September 2010. Paper 750.

[6] A. Kern, C. Schelthoff, and M. Mathieu, „Calculation of interception efficiencies for air-terminations using a dynamic electro-geometrical model“, Proc. of 11th International Symposium on Lightning Protection (SIPDA), Fortaleza (BR), October 2011. pp 44 – 49.

[7] Z.A. Hartono, and I. Robiah, “The collection surface concept as a reliable method for predicting the lightning strike location”. 25th International Conference on Lightning Protection (ICLP), Rhodes (GR), September 2000. pp. 328 – 333.