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Field computational method as a tool for modification of lightning protective zones

***Abstract**.The paper presents one of the most important question relating to the protection of buildings against the effects of lightning namely the efficiency of air terminals used for lightning discharge interception. Considerations based on studies of model and simulation of electric field distribution.Results of examinations presented in this paper rely on many case studies, depends on various geometry of earth placed objects, step leader charge or it's placement in space. All of the calculations where made with computer PC with installed software called Comsol Multiphysics, based on electrostatic method (3D).*

***Streszczenie.** W referacie przedstawiono jedną z najważniejszych kwestii dotyczących ochrony obiektów budowlanych przed oddziaływaniem wyładowań atmosferycznych, a mianowicie skuteczność wybiórczości tych wyładowań przez stosowane w tym celu zwody. Rozważania oparto na badaniach modelowych i symulacyjnych rozkładu natężenia pola elektrycznego. W badaniach rozpatrzono wiele przypadków uwzględniając między innymi geometrię obiektów naziemnych, ładunek lidera skokowego oraz jego położenie w rozpatrywanej przestrzeni. Obliczenia zostały wykonane przy użyciu komputera PC i programu do obliczeń polowych Comsol Multiphysics. (**Metoda obliczania pola jako narzędzie do modyfikacji piorunowych stref ochronnych**)*

Keywords: lightning discharge, downward step leader, electric field, rolling sphere method.
Słowa kluczowe: wyładowanie piorunowe, lider skokowy odgórny, pole elektryczne, metoda toczącej się kuli.

Introduction

The efficiency of air terminals used for lightning discharge interception belongs to the present-day and most important questions to structure protection against these discharges [1], [2].

There are different methods for dimensioning of protection zones created by air terminals but only none of them can be considered as most reliable. The mesh method is more intuitive one than based on a credible theory. It was based on the Faraday's cage principle and is now often verified by means of the so-called Rolling Sphere Method (RSM) [3].

The protection (or shielding) angle method is a result of influence of different theories, such as the theory of F.W. Peek, and A. Schwaiger [4], [5], and is supported by field observations and also by laboratory test results, which - as is well known - can not be transferred to real conditions. This method evokes serious reservations and like the mesh method is often verified by RSM, which is most versatile and least controversial at dimensioning of protection zones. It is also derived from these theoriesand leads undoubtedly to excessive restrictions in assessing the scope of protection, because it does not takes into account the phenomenon of mutual shielding grounded conductive structures and their impact on the design of the electric field distribution around the shielding and shielded structures.

According to the RSM every point of contact surface of the rolling sphere with protected object (see 1, 2, 3 in Figure 1a) is exposed to direct lightning strikes. So in order to avoid such strikes the structure contact points Z (Fig. 1b) should be equipped with appropriate air terminals. It has to be noted, that around the contact points different conditions influencing the lightning interception may exist. Despite identical location of these points the differently shaped surfaces in their environment can significantly affect the distribution of the electric field, and thus the selectivity of discharge. It is, after all, the rule that the electric field strength increases with decreasing radius of curvature of the object surface and its higher elevation above the earth's surface. For example, the electric field at points 2 and 3 on the contact surface of a sphere with a flat or slightly curved surface of the object (Fig. 1a) is much smaller than the field strength at the same points of the sphere of its contact with the sharp edges of objects (Fig. 1c). With the increase of the electric field at points 2 and 3, after the replacement of the flat and gently rounded surfaces by sharp edges, the formation of upward discharges, and thus the attraction of downward leaders become much more probable. However it is not indifferent whether the points 2 and 3 are accompanied by additional points, in particular by above located points like point 1 in Figure 1, or not. The existence of these points creates a shielding factor, for the lower points, and reduces the electric field intensity around these points. As a result, the RSM leads to excessive reduction of protection zones.

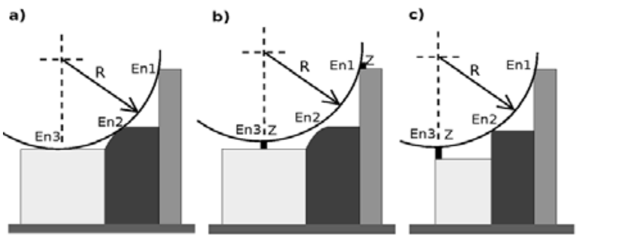

Fig. 1 Illustration of local conditions affecting the interception of lightning discharges by RSM

Investigations of the electric field distribution around the structures of different heights and mutual locations do not allow to confirm validity of the assumptions adopted in the RSM. It can not therefore confirm the rule that each point of the sphere sutface in contact with the ground structure can be struck by lightning with equal probability. A modification of this rule seems to be necessary and it may be made by analyzing of the electric field distribution at the tops of structures being in contact with rolling sphere surface and higher ones. For this aim the modeling and simulation researches have been performed and based on a R. Thottappillil's model [6], taking into account different factors, such as: the geometry of the protected objects, electrical charge of stepped leader, (spatial distribution) and striking distance. Appropriate simulations were carried out using the Comsol Multiphysics computer program.

Assumptions of analytical model

The model that was adopted for the researches is shown in Figure 2. It was assumed that the leader step is initiated in the middle of the plane with dimensions of 2000 x 2000m. This plane represents charged cloud base at a height of 2 km above the ground surface. The stepped leader electric charge is linearly distributed along the entire channel. In the final phase of the leader development, the linear charge density corresponds to the smallest peak value of the expected return stroke currents amounting to 3 kA.

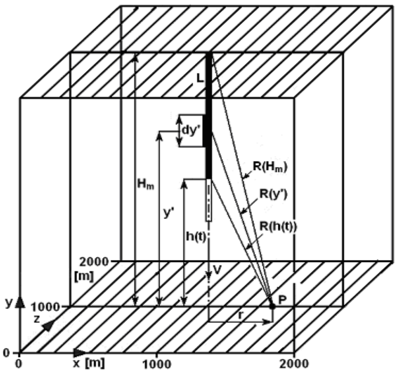

Fig. 2 Sketch of model adopted for research

The electric field strength in the space between the lower end of the developing downward leader (its head) and the ground surface, at the start instant of the leader last step, can be described by the general equation as follows:

$$\text{(1)} \qquad \mathbf{E}(x,y,z,t) = -grad\varphi - \frac{\partial \mathbf{A}}{\partial t}$$

where:***E(x,y,z,t)*** - the electric field strength at time *t* in the point with coordinates *x, y, z; φ,* ***A*** - delayed scalar and vector potentials respectively called at that point by the leader's charge with linear density.

For the study of electrical field distribution according to equation (1) a simplified R. Thottappillil's method [6] has been applied. Moreover the field component associated with the movement of charge in the leader channel has been neglected and only the vertical component of the electric field associated with this charge has been taken in account. The charge is determined by the so-called normalized of time instants. Vectors of the electric field strength at any given instant may be considered as corresponding to a certain quasi static system state. In this case, the equation describing the normal component of the electric field at the point $P(x, y, z, t) = P_y(r, t)$ of Figure 2 can be represented as [6]:

$$\text{(2)} \quad E_y(r,t) = \frac{1}{2\pi\varepsilon_0}\int_{h(t)}^{H_m}[y',t-\frac{R(y')}{c}]dy' - \frac{1}{2\pi\varepsilon_0}\frac{H}{R^3(H_m)}\int_{h(t)}^{Hm}\rho_l[y',t-\frac{R(y')}{c}]dy'$$

where: $R(H_m) = (H_m^2 + r^2)^{0,5}$ - the distance between the beginning of the leader and the point *P; R(h(t))* - the distance between the leader head and the point *P;* whereas *h (t)* – the distance resulting from the equation:

$$\text{(3)} \qquad t = \frac{H_m - h(t)}{v} + \frac{\sqrt{h^2(t) + r^2}}{c}$$

where: *v, c* - respectively the speeds of the leader development and the electromagnetic wave in air.

The first term in formula (2) expresses the electric field changes dependent on the charge in the developing leader's channel and the second term - the electric field changes dependent on the cloud charge.

Assuming that the value of the charge in the thundercloud is many times greater than the leader channel, and that the changes of this charge associated with its depletion influence to a small extent the value of the electric field in the space between leader's head and the ground surface, equation (2) can be simplified to the form:

$$\text{(4)} \qquad E_y(r,t) = \frac{-1}{2\pi\varepsilon_0}\int_{H_m}^{y_t}[\frac{y'}{R^3(y')} - \frac{H_m}{R^3(H_m)}]\rho_l(y',t)dy'$$

Finally, assuming that a permanent charge density in the leader's channel $\rho_l(y',t) = \rho_l = const.$ it is possible to convert the equation (4) as it follows:

$$\text{(5)} \quad E_y(r,t) = (\frac{\rho_l}{2\pi\varepsilon_0 r})[\frac{1}{(1+y_t^2/r^2)^{\frac{1}{2}}} - \frac{1}{(1+H_m^2/r^2)^{\frac{1}{2}}} - \frac{(H_m - y_t)H_m}{r^2(1+H_m^2/r^2)^{\frac{1}{2}}}]$$

where: $y_t = H_m - vt$ – the height of the leader's head at the instat t; ν - its velocity, assumed to be constant.

These equation has been accepted as a basic tool for field calculation during the simulations.

3. The simulation studies

As it was already stated, the Rolling Sphere Method (RSM) is based on the idea that the every point of the ground structure beeing in the contact with the rolling sphere can be struck by lightning with the same probability. In order to show that this idea is not quite precise adequate simulation studies has been performed by means of Comsol Multiphysics computer program. An example of the electric field distribution in points of the space between leader head and conducting grounded structures is shown in Fig. 3

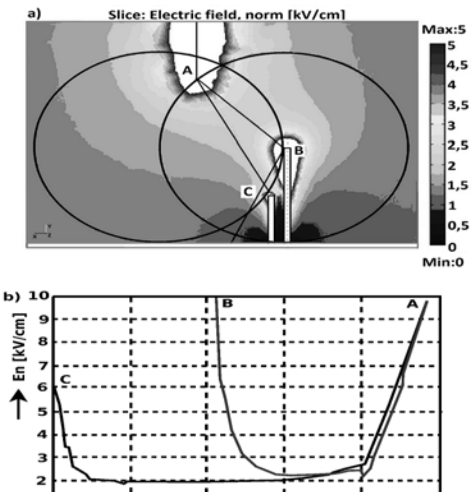

Fig.3 Field distribution: a) colored chart, b) field distribution between points A-B and A-C

Special attention has been paid to the values of electric field at the tops of conducting grounded structures located in series under the rolling spheres with the radius of 20 m, as it is shown in Figures 4 – 6. This radius corresponds to the least peak value of the lightning current in order to assure the greatest penetration of lightning strikes. Highest structure represents the air termination and the other ones (being in contact or not with the sphere) are to be protected. Simulations has been performed for the leader last step starting instant. Calculated values of electric field (i.e. its vectors En) at the structure top points are given, in Figures 4 -6 above these points.

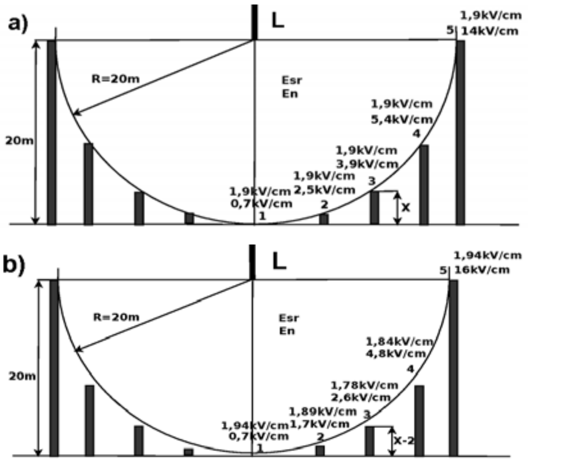

Fig.4 Examples of computing systems with structures: a) being in contact with sphere, b) lower in points 2, 3, 4; En – electric field vector values (black) and the Esr - average electric field value (blue)

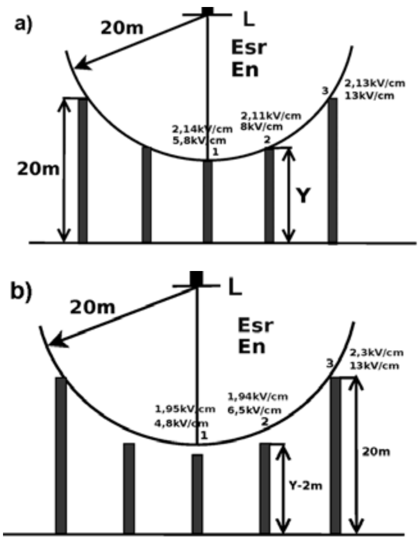

Fig.5 Examples of computing systems with structures: a) being in contact with sphere, b) lower in points 1, 2; En – electric field vector values (black) and the Esr - average electric field value (blue)

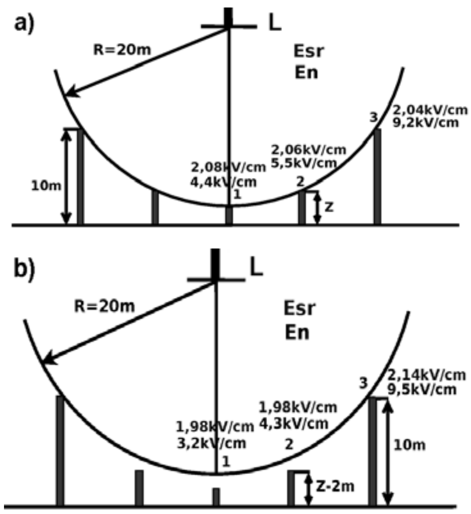

Fig.6 Examples of computing systems with structures: a) being in contact with sphere, b) lower in points 1, 2; En – electric field vector values (black) and the Esr - average electric field value (blue)

Simulation results and conclusions

The results of the electrical field simulations may be summarized as folows:

1) If the leader head is located at the same striking distance *R* from the top of highest structure (point 5 in Fig.4a, air termination) and from the ground surface, what is the worst case from the air termination effectiveness point of view , the field strength at this top can reach values at the level of 16 kV/cm.

2) If the tops of neighboring structures 2, 3, 4 are located at the same distance *R* from the leader head, the field strength at these tops significantly decreases with distance from the air termination. At the level of ground surface the electric field strength reaches the value barely equal 0.7 kV/cm (point 1 in Fig. 4a). It means that:
- air termination shields the surrounding structures,
- the mean value of the electric field between the leader head and the structure tops (Fig. 4a), can not be used as adequate criterion of lightning interception, because different electrical condition at these tops (shielding, field reduction, upwards leader elimination) may have significant influence,
- local elctrical conditins, when disregarded, lead in RSM to distinctly underestimated protection zones.

3) The intensity of electrical field significantly decreases at the structure top to be protected, when its distance from the rolling sphere surface increases (see points 2, 3 and 4 in the Fig. 4b as well as point 2 in Fig. 5b and 6b) when the difference between structure's heights and the distance between external structures (air terminations) decrease (Fig.5a), then the difference between field strength valuesat the structure also decreases, and so:
- the shielding effect is observed,
- the reduction of protection zone by rolling sphere decreases.

4) The structure heights above the ground surface have an impact on shielding effect and on the underestimation of protection zones. The shielding effect and underestimation of protection zones decreases with the reduction of structure heights (compare Fig.6a with Fig. 5a).

5) The dimensioning of protection zones on the base of mean values of the electric field strength is not adequate, because it does not allow to take in account the impact of:
- the shielding phenomenon,
- the differences in the distance between the structures and their heights from the ground level.

Concluding, it should be stated that the rolling sphere method, although universal, can not be accepted as perfect one and needs to be modified.

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