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

Abstract. The paper presents one of the most important questions 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, depending on various geometry of earth placed objects, step leader charge or its placement in space. All of the calculations were 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 wyborczości tych wyładowań przez stosowane w tym celu zwody. Rozważania oparte na badaniach modelowych i symulacyjnych rozkładu napięcia pola elektrycznego. W badaniach rozpatrzono wiele przypadków uwzględniających 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 pionowych stref ochronnych)

Keywords: lightning discharge, downward step leader, electric field, rolling sphere method.
Słowa kluczowe: wyładowanie pionowe, lider skokowy odgórny, pole elektryczne, metoda tocącej 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. Schweiger [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 theories and leads undoubtedly to excessive restrictions in 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.

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 surface 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. Thottapillil’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.

Assuming that the value of the charge in the leader’s channel and the second term - the electric field changes dependent on the charge in the developing 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:

\[
E_y(r,t) = -\frac{1}{2\pi\varepsilon_0} \left( \int \frac{\rho_l(y',t)}{R^3(y',t)} dy' \right) - \frac{1}{(1+H^2_{m}/r^2)^{3/2}} \int \frac{\rho_l(y',t)}{R^2(y',t)} dy' \frac{H_m}{r^2} \]

where:

\[
\rho_l(y',t) = \rho_l(r',t) \Delta \text{y}
\]

\[
y = H_m - v t - \delta
\]

where: \(y_i = H_m - v t\) - the height of the leader’s head at the instant t; \(v\) - its velocity, assumed to be constant.

These equations have 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 being in 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 have 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.
Simulation results and conclusions

The results of the electrical field simulations may be summarized as follows:
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 electrical conditions, 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 values at 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.

REFERENCES

[3] IEC 62305-3 - Protection against lightning - Part 3: Physical damage to structure and life hazard

Author: mgr inż. Przemysław Sul, Politechnika Warszawska, Zakład Wysokich Napięć i Kompatybilności Elektromagnetycznej, IETiSIP PW, ul. Koszykowa 75, 00-662 Warszawa, E-mail: przemyslaw.sul@ee.pw.edu.pl