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Factors affecting the assessment of the selectivity of lightning impact for dimensioning the areas protected by air terminals

Abstract. *The factors affecting the selectivity of lightning discharges by air terminations are analyzed in the paper. For this aim the simulations of electric field distribution around the surface of conductive structures have been performed. The need for correction of normative methods for air termination dimensioning has been confirmed and the way for this correction depending on the lightning polarity has been proposed.*

Streszczenie. *W artykule analizowane są czynniki mogące mieć wpływ na wybiórczość wyładowań piorunowych przez zwody. Dokonano symulacji rozkładu natężenia pola elektrycznego wokół przewodzących struktur naziemnych. Stwierdzono potrzebę i zaproponowano sposób korekty normatywnych metod wymiarowana stref chronionych w zależności od biegunowości piorunów. (**Czynniki wpływające na ocenę selektywności uderzenia pioruna przy wymiarowaniu przestrzeni chronionych przez zwody**)*

Keywords: lightning discharge, electrical field intensity, rolling sphere method, protected zone, spark-gap coefficient
Słowa kluczowe: wyładowanie piorunowe, natężenie pola elektrycznego, metoda toczącej się kuli, strefa chroniona, współczynnik przerwy iskrowej

Introduction

A most important role of air terminations, as a part of lightning protection system (LPS), is to provide effective interception of lightning discharges [1], [2]. Such interception depends on the air termination positioning, which - according to the normative requirements [5], [6] - may be carried out using three methods. One of them, namely Rolling Sphere Method (RSM) has been suggested normatively as a most reliable one [6], but this suggestion arouses significant controversies [1].

A main objection is related to its basic criterial parameter, namely with the average value of electrical field distributed between lightning leader head and the prospective point to be struck regardless of its local conditions. However, these conditions in a number of cases appears to be essential [2], [3], because there is the dependence of electric field distribution on such factors as: the mutual shielding of over-ground conductive elements, diverse geometry of structures and their surroundings as well as the presence of additional electrode, i.e. the earth surface, in the arrangement of leader – over-ground structure. The leader polarity is also significant. The more insightful considerations, which have been here undertaken on the influence of these factors on the distribution of electric field intensity, allow confirming the validity of raised objections and indicating the need to establish a more criterial parameter. The attention is attracted here to absolute values (modules) of electric field and their distributions along the surface of the over-ground structures, as well as to effects of - already mentioned - additional electrode quantified by means of so-called spark-gap factor.

Skipping the influence of local conditions on the distribution of electric field intensity, and consequently, on the ranges of air termination protected zones, can lead to the oversized or undersized zones. It is obvious that the increase of absolute value of the electric field intensity at a specific point of the structure means also the increase of the probability of lightning strike to this point. Thus, the knowledge of the distribution of the absolute values of the electric field intensity, just before the return stroke, allows identifying a prospective point of lightning strike. Surely, it cannot be a point with a little value of electric field intensity. Undoubtedly, this value depends on factors already mentioned and particularly on the additional electrode and its quantitative influence, which in turn depends on the polarity of the leader and the value of the corresponding coefficient of the spark gap. In special cases it may also be important to assign the role of reference plane for the surfaces positioned above ground and to be little the role of space charges appearing in the vicinity of prospective points.

In order to discern the scale of impact of these factors on the selectivity of lightning strikes by air terminations, or otherwise, on the ranges of protected zones, appropriate computer simulations were carried out using the program Comsol Multiphysics. On the base of obtained results appropriate conclusions have been formulated.

Basic assumptions

The subject of the simulation is the distribution of electric field caused by the charge of lightning leader (L) in the immediate environment of a structure exposed to lightning strikes. The leader is initiated at the base of the thunderstorm cloud (CB) and descents vertically to the earth surface (ES), as it can be seen in the simplified arrangement of cylindrical coordinates ($y,\ r$) in Fig. 1, mapping a model proposed by R. Thottappillil, V.A. Rakov and M.A. Uman [4].

Cloud basis with its charge is located at a height H_m = 2 km from the earth's surface. The leader charge in entire channel is linearly distributed and its density $\rho_1(y',t)$ = 8,02 10^{-5} C/m at the time instant t, just before the return stroke, corresponds to the smallest peak value of the current I = 3 kA, which is to occur with return stroke in point $P(y,r)$. Adopted current value means that the last step of the leader has a length of $h(t)$ = 20 m. Of course, if the leader is developing over the structure, the height $h(t)$ increases by the height of this structure, but the intermediate position of leader head is also taken into account.

The analysis of the arrangement has been aimed to recognize the electric field distribution, caused in different points $P(y,r)$ on the earth surface and on the surface of over-ground conductive structures, by the leader charge at the instant of its start to the last step. Selection of this instant means that the influence of charge movement in the channel is neglected and that the distribution of the field intensity at the instant of this start can be regarded as quasi-stationary. Similarly, due to the fact that the charge of thunderstorm cloud is positioned at a considerable distance H_m = 2 km from the place of considered field intensity, its effect on the field distribution may also be omitted.

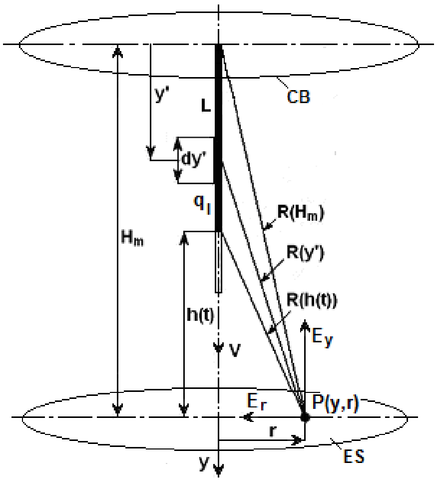


Fig.1. The model of arrangement adopted to investigations; L - leader aiming at the point *P*(*y,r*) positioned on or above the ground surface (ES); y, r - coordinates of arrangement, CB- thunderstorm cloud base, L - leader, q_l - linear density of leader charge, v – leader development velocity, H_m – height of the thunderstorm cloud basis, h (t) - the height of the leader head.

The electric field vector E_p^- at each point $P(y,r)$ is directed to the leader head. The components E_y and E_r of this vector, considered in the arrangement as shown in Fig. 1, may be expressed by following relations:

$$(1)\quad E_y \approx \frac{q_l}{4\pi\varepsilon_0}\left[\frac{1}{\sqrt{(H_m - h_t - y)^2 + r^2}} - \frac{1}{\sqrt{y^2 + r^2}}\right]$$

$$(2)\quad E_r \approx \frac{q_l}{4\pi\varepsilon_0 r}\left[\frac{H_m - h_t - y}{\sqrt{(H_m - h_t - y)^2 + r^2}} + \frac{y}{\sqrt{y^2 + r^2}}\right]$$

in which: ε_0 - permittivity of vacuum, and the meaning of remaining symbols is the same as in the caption of Fig. 1.

As a measure of the intensity of the electric field, occurring at particular points of the structure exposed to the lightning strikes, the absolute value E_p (module) of the vector E_p^- has been taken in account. It is associated with its components E_y and E_r by the following relationship:

$$(3)\quad |E_p| = \sqrt{E_y^2 + E_r^2}$$

This relationship has been recognized as a key element of simulation procedures applied for estimating the distribution of the electric field intensity around the selected surfaces of the over-ground structures. A care was taken to select the structures allowing to demonstrate that in the distinct points of the structure there are significant differences between the mean values of the electric field intensities and their modules, and that the distributions of the electric field intensity depends, among others, on the height and the shape of the investigated over-ground structure as well as on its location in relation to the earth surface and to the leader head. The aim was also to demonstrate the leader polarity role, which this polarity may play in the distribution of the electric field intensity. However, as it is known, the electric field distribution is - in the Comsol Multiphysics computer simulation program - mapped using the finite element method (FEM), which is not conducive to accomplish such a task. Therefore it aroused an additional necessary to reach for the relationships based on the laboratory tests of spark gaps.

A significant advantage of downward lightning negative discharges, covering 90% of all discharges, points to the desirability of drawing the attention primarily on these discharges. However, this does not mean sacrificing the reference to the role, playing by the positive polarity of downward lightning discharges, but this reference is - just as in the case of negative polarity - requires reaching for relationships based on laboratory tests of spark gaps.

Distributions of electric field intensity - modules and average values of field intensity

Investigation of the difference between the mean values of electric field and its modules, as well as a study of the over-ground structure height influence on these values was performed in the arrangement from Fig. 2. The location of the leader head was adjusted to the height of the lowest over-ground structure and the heights and placement of remaining structures were addicted to the radius *R* of rolling sphere.

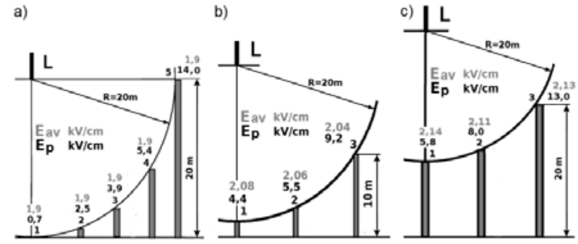


Fig.2. Comparison of field modules E_p at the tops of vertical rods, distributed along the rolling sphere surface, with average values E_{av} of the field between these tops and leader head placed on the height: a) 20 m, b) 22, c) 31 m. .

When analyzing obtained results, it should be noted that the average values of the electric field intensity are slightly increased with the growth of the leader head distance from the earth surface, and they are not practically changed if the structure increase along the contour of the rolling sphere. In contrast, the modules of electric field intensity in both cases are subjected to substantial growth. At the least distance of the leader head from the ground surface (*r* = 20 m) the discrepancy between the module values of the field intensity along the surface of the rolling sphere exceeds by far the level of the magnitude order. With increasing distance from the ground to the leader head the values of modules are becoming more comparable. Obtaining identical values of the modules would require from smaller structures to penetrate into the interior of the rolling sphere at the height of more than half of its radius *R* as can be seen in Fig. 3. It reveals the phenomenon of mutual shielding over-ground structures. For example, the rapprochement of the top of structure 4 to the top of the structure 5 results in reduction of the module from the value E_p = 14.3 kV/cm to the value E_p = 13.8 kV/cm.

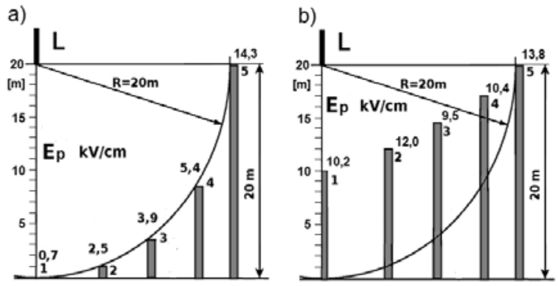


Fig. 3. Comparison of field modules at the tops of vertical rods: a) reaching the surface of rolling sphere, b) incoming into the sphere

Distributions of electric field intensity - modules and geometry of endangered structures

The investigations of the influence of endangered structure's geometry on the distribution of the modules of electric field intensity have been made in the arrangements shown in Fig. 4 and in Fig. 5.

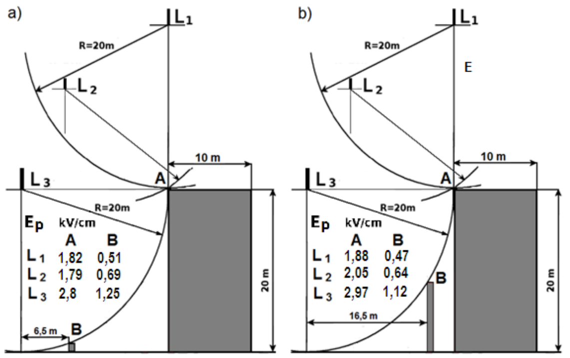
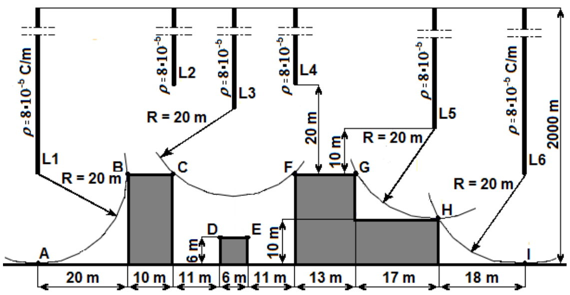


Fig 4. Values of field modules caused, by different position of leaders, at the apex point of a structure and protected external element being in the horizontal distance of: a) 6,5 m and b)16,5 from the leader



Leader position	Intensity of electric field [kV/cm] in selected points of arrangement								
	A	B	C	D	E	F	G	H	I
L1	0,607	2,686	1,179	0,195	0,176	0,591	0,490	0,210	0,110
L2	0,206	1,453	1,441	0,252	0,248	0,900	0,653	0,280	0,135
L3	0,176	1,319	1,500	0,331	0,297	1,371	0,948	0,323	0,157
L4	0,146	0,862	1,233	0,257	0,277	1,184	1,015	0,373	0,181
L5	0,112	0,722	0,715	0,173	0,163	0,829	1,430	0,778	0,327
L6	0,098	0,502	0,616	0,141	0,133	0,680	1,075	0,777	0,653

Fig. 5. Distribution of field modules caused by different leaders at the apex points of structure arrangement

In the first case the three positions of leader heads have been distinguished, namely at the ends and in the middle of the horizontal distance equal to the radius of rolling sphere R = 20 m. Whereas in the second case the six characteristic leader positions and the prominent points of three structures included into arrangement under consideration have been selected. Module values of electric field intensity at these prominent points are affected from different distances by the selected leaders and structure components. The results of such interactions allow confirming some regularities.

The module values of electric field intensity resulting from the arrangement of Fig. 4 allow confirming the shielding effect. As can be seen, the top of structure B on the right side of Figure 4, despite a much greater height than the height of the structure B on the left side, is characterized by a lower value of the electric field intensity than the top of the structure B, which is undoubtedly the result of more effective its shielding by close structure A. Disclosed herein is also the influence of the structure dimensions, as can be seen here, a significant reduction in field intensity compared with its value on the rod type structure in Fig. 3a). This confirms the smaller value of the electric field intensity at the point F in Fig. 5, than at the point C, although the leader interaction in these two points is identical. The structure dimensions have here and in other places (e.g. in point G) a clear influence.

Leader polarity and spark gap coefficient

Due to the difficulties associated with the involvement of the leader polarity into investigations based on simulations it was necessary to reach for the results of laboratory tests. They are shown in Fig. 6 with an indication the polarity of the point electrode, mapping the leader head. Curve 1 refers to the arrangement, in which h = 0, and hence to the point-plate arrangement, and the curve 2 refers to the arrangement in which $h = a$, and therefore to the point-point grounded arrangement. It is worth to mention that the increase of height h in relation to length a of spark gap causes the decrease of arrangement withstand voltage when the upper electrode is of negative polarity (see curve 3 in Fig. 6b), but when this electrode is of the positive polarity then the withstand voltage increases up to and above the values indicated by the curve 2.

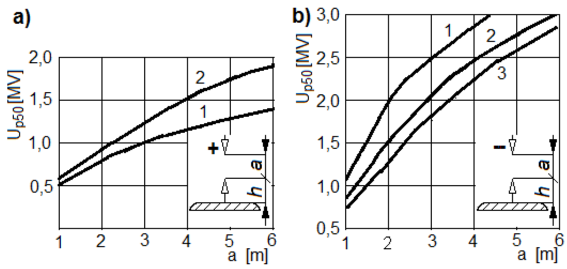


Fig. 6. Influence of point electrode polarity on the point-plate and point-point grounded electrode arrangement

Comparing the curve shapes presented in Fig. 6b) with a given in Fig. 2 and 3 module values of electric field intensity a certain compatibility can be observed. Namely, with an increase of the over-ground structure there is a growing of both the module value and the probability of sparkover appearing, so in this way the growing of the probability of the lightning stroke into this structure. The situation in the arrangement with positive point electrode is reversed. With the increase of the over-ground structure (i.e. the earthed electrode) the probability of sparkover decreases what causes the reduction of module value of the electric field intensity.

The consequences of the observations as given above may be in the practice of lightning protection very significant. They concern the range of the zone protected by air terminations. This range in the case of lightning with negative polarity (approx. 90% of all lightning) is greater than those established by RSM, and in the case of lightning with positive polarity it is reduced.

The ranges of the protected zone established by RSM can be - in the case of lightnings with negative polarity - corrected using the spark gap coefficient in the following analytical form

$$k = 1{,}42 - 0{,}84\frac{h}{h+R} \tag{4}$$

in which: R - radius of the rolling sphere and h - the height of the protected over-ground structure.

The correction effect of the protected zone range has been shown on Fig. 7. It is based on the transfer of the rolling sphere from the position marked with a dashed line to the position marked with a continuous line. It should be noted that the increase of the h value up to the value equal R reduces the value of the coefficient k to the unity.

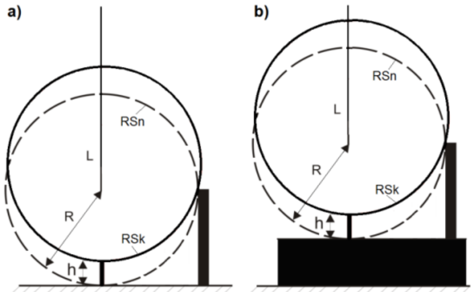


Fig. 7. Graphical explanation of the correction of protected zone range created by vertical air termination positioned: a) on the ground surface, b) on the building roof; RSn - the rolling sphere placed by RSM, RSk – rolling sphere in corrected position.

The intention for Fig. 7b) presentation is the need to underline the special situation for air terminations, which are positioned on the roof, or for the structure conductive elements, which are used as the natural air terminations to protect other roof devices. Now, the roof surface may be used as the reference plane only, when it is metallic and earthed. If it doesn't exhibit these features, the earth surface should continue its task as a reference plane. Other grounded metallic elements existing on the roof shall be treated as natural air terminations.

Possible influence of space charges

The inference on the possibility of increasing the range of the protected zone in the case of the leader with negative polarity doesn't imply the endorsement for so-called active air terminals, to which are wrongly attributed much larger protected zone ranges than standard ranges. Just the opposite, the basis of this inference, explained in Fig 8, indicates the need to disqualify the whole idea of such "active air terminations". Namely, with the appearance of the ionization at the air termination with positive polarity, the free electrons (as much more mobile than positive ions of the molecule) are immediately absorbed by this air termination. Remaining there the positive charge increases together with the radius of its space and in this way it reduces over the air termination the electric field intensity, what is shown on the right side of Fig. 8. In such conditions it is impossible to speak about the appearance and accelerated development of upward streamer from this air termination.

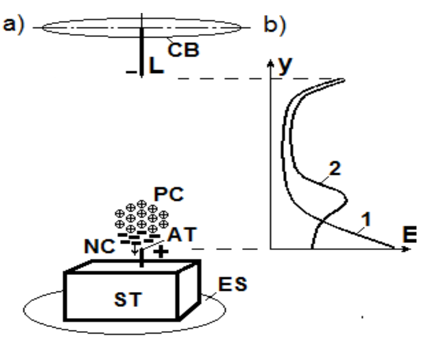


Fig. 8. Illustration: a) arrangement leader (L)-air termination (AT) and b) electric field intensity distribution (E) in this arrangement; PC - positive space charge, NC - vanished electrons into AT, CB – thunderstorm cloud base, ST – structure, ES – earth surface, Curves 1 and 2 - field distribution before and after the ionization and space charge appearance

Practical observations show that the earliest development of upward streamers appears from the air termination top with optimal radius length of its curvature.

Conclusions

On the base of performed simulations and considerations the following statements may be recognized as appropriate:

- rolling sphere method, and thus the method of protective angle, should be based not on the average value of the electric field intensity distribution, but on its absolute value (module) appearing in prospective point of lightning strike in the instant just before the return stroke;
- distribution of electric field intensity modules are critically dependent on such factors as: the height of the prospective lightning impact points counted from the ground surface, the geometry of the structure exposed to lightning strikes and the polarity of the lightning leader;
- the protected zones determined by the rolling sphere method should be adjusted by means of spark gap coefficient for given polarity of the downward lightning leader;
- increase of the range of protected zone created by vertical air terminations in relation to the range obtained by RSM cannot be identified with the increase attributed to the so-called "active air terminations".

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