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Determination of the probability of a lightning strike in the elements of the object taking into account the statistical distribution of the current value

Problem. *Modern international standards in the field of lightning protection, when assessing the probability of a lightning strike into an object, do not take into account the statistical distribution of the lightning current.* ***Goal.*** *Justification of the expediency of taking into account the statistical distribution of the lightning current with a determined probability of lightning striking the elements of the object, and the effectiveness of the application of the improved «rolling sphere» method.* ***Methodology.*** *Method of mathematical modeling, based on RSM with additional consideration of the probability distribution of lightning current.* ***Results.*** *The expediency of taking into account the statistical distribution of lightning current at the determined probability of lightning striking the elements of the object has been proven. The effectiveness of the improved «rolling sphere» method, implemented in the form of a computer program, which takes into account the given probability distribution of lightning current in the range from 2 kA to 200 kA, has been proved. The expediency of introducing the concept of «average value of the area of the collection area» is substantiated, taking into account the probability of lightning with a current in a given range. It has been established that the application of the standardized formula leads to a significant (many times) overestimation of the predicted number of lightning strikes to the object, if the height of the object exceeds 20 m. The reasons for the difference, according to the author, are due to the following properties of the standardized methodology: usually, the real shape of the object is not taken into account; statistical distribution of lightning current is not taken into account; it is based on the results of experimental studies obtained mainly for mast or rod-type objects in laboratory conditions with a limited discharge interval.* ***Practical value.*** *This approach will provide an opportunity to optimize the layout of lightning arresters during the restoration of objects, taking into account green reconstruction. The obtained results are proposed for consideration by the Technical Committee TC 81 IEC for inclusion in the next editions of the standards.* References 21, table 2, figure 1.

Key words: **lightning protection, risk assessment, RSM - Rolling Sphere Method, object of arbitrary shape, probability distribution of lightning current, collection area.**

В роботі розглянуто застосування методу «сфери що котиться» до об'єктів інфраструктури у вигляді території, яка включає будівлі та споруди довільної форми. Запропоновано алгоритм урахування статистичного розподілу ймовірності сили струму блискавки для визначення ймовірності влучення блискавки у елементи об'єкту. Визначено, що не урахування цього аспекту у сучасних нормативних документах, призводить до суттєвих помилок. Такий підхід наддасть можливість оптимізувати схему розміщення блискавкоприймачів під час відновлення об'єктів з урахуванням зеленої реконструкції. Бібл. 21, табл. 2, рис. 1.

Ключові слова: **блискавкозахист, оцінка ризику, RSM – метод сфери що котиться, об'єкт довільної форми, розподіл ймовірності сили струму блискавки, площа стягування.**

Problem definition. The widespread use in production and everyday life of various technical means equipped with electronic elements of control, decision-making and control requires a more careful approach to determining the need to equip objects with protection systems (Lightning Protection System – LPS) against the negative consequences of lightning strikes. Such systems must provide a given probability of lightning interception and reduction of voltage and current levels arising in the object's galvanic connections as a result of a lightning strike. International standards IEC series 62305 [1-3] require the implementation of such an assessment, but the methods proposed in them, based on the definition of protection zones, do not allow to solve the problem in full. These standards provide zones only for a limited group of lightning arresters, and do not take into account the probability distribution of lightning current, the presence of other buildings and structures that are nearby. The regulated Rolling Sphere Method (RSM) can potentially be used to refine the calculated estimate of the probability of lightning striking the elements of the object.

Analysis of the latest research and publications. The modern approach to determining requirements for LPS of buildings and structures is regulated by international standards [1-3]. The standard [2] defines the algorithm for assessing the value of the risk due to a possible lightning strike to a building or structure, etc. (hereinafter referred to as the object). The risk *R*, defined as the probable average annual loss at the facility due to lightning flashes, depends on [2]:

- the annual number of lightning flashes affecting the object;
- the probability of damage from the action of one of these lightning strikes;
- the average number of indirect losses.

Based on the results of the risk assessment, a decision is made about the necessity of setting up the LPS system and the requirements for its level of protection. Ground-level flashes of lightning acting on an object can be divided into:

- flashes that hit the object;
- flashes that hit near the object, directly on the power line, telecommunication line, or near the lines.

The number of lightning strikes affecting an object depends on the density of ground-level lightning flashes in the region where the object is located. In item 4.1.1 [2] it is determined that the return current of lightning is the primary source of damage. Among the factors that affect the risk components is the number of dangerous events [2]. The average annual number of dangerous events *N* that affect an object due to lightning flashes depends on the thunderstorm activity in the region where the object is located and on its geometric and physical characteristics. To calculate the value of N, the density of ground-level lightning flashes N_G is usually multiplied by the equivalent area of the assembly of the building (structure), taking into account the correcting coefficients.

The density of ground-level lightning flashes N_G is the number of lightning flashes per 1 km^2 during the year. This value is usually available from lightning location networks and is adjusted annually. In the absence of data on N_G values, for the middle latitudes of the northern hemisphere of the Earth, this indicator can be estimated as [2]:

$$N_G \approx 0{,}1\ T_D, \qquad (1)$$

where T_D is the number of thunderstorm days during the year (which can be obtained from isokeraunic maps).

It should be noted that nowadays there are more accurate methods for determining N_G, so the use of thunderstorm days is proposed [4] to be changed to:

$$N_G = 0{,}25 \cdot N_t,$$

where N_t is the total density of optically detected flashes per km^2 during the year, obtained from [5].

The standard [3] regulates the possibility of using the RSM method for the construction of LPS protection zones. The radius of the sphere depends on the class of the building. It is clear that class I requires the highest level of protection, so the radius of the sphere is defined as the smallest (equal to 20 m). Examples of the application of this approach are presented in [6-11]. It is noted that the calculated zones differ from the zones determined by the protective angle method. This contradiction requires an assessment of which method is more correct. As a result of many years of discussion, the possibility of using both methods has been determined, and the choice is made by the designer. This happened because none of these methods has evidence of unconditional reliability. Protection zones based on the protective angle method cannot be substantiated by laboratory experiments, the results of which are ambiguous. It was established that the results of model tests strongly depend on the length of the spark discharge used, on the polarity of the pulse voltage and its time parameters. In addition, the protective properties of the zone are not confirmed by the experience of operating lightning arresters of different heights.

The RSM method has significant advantages because it allows to calculate zones for objects of arbitrary shape, to take into account the collective action of lightning arresters, including natural ones. Calculations confirm the higher efficiency of the system of lightning arresters compared to a single one, due to the reduction of the collection area. However, the method in its standardized form does not take into account the presence of opposing leaders from the object elements. Which definitely affect the location of the lightning strike, but also have a stochastic nature. Attempts to take into account opposing leaders are presented in [12, 13]. The obtained results have a certain value for the development of methods, but have not yet been reflected in standards. Therefore, the influence of opposing leaders cannot be taken into account by LPS designers.

It should be additionally noted that the RSM method allows taking into account any radius of the sphere, which is determined by the lightning return current. It is this nuance that is used in the work, which is described below. For a clear understanding of the content of the work, let's discuss a number of important points.

Up to the orientation height H_{at}, lightning trajectories are not deterministic and their heads fill the orientation plane with a uniform density. Then everything depends on the state of the earth's surface. Lightning is most likely to go further down the shortest distance, but even at laboratory intervals, the spread of long spark trajectories and the spread of breakdown voltage are clearly recorded. The lightning channels going to the lightning arrester and to the undisturbed surface of the earth are, as a rule, distant by a distance of tens of meters or more. Therefore, the mutual influence of their electric fields on each other is insignificant, and the development of each of the channels should be considered independent of the others. Probability theory is well developed for such processes. According to its laws, the probability of breakdown of one of the two discharge gaps – to the lightning arrester and to the surface of the earth, in addition to geometric dimensions, is determined by a single parameter – the breakdown voltage standard σ, which is an orientation standard, it changes little with the length of the multi-meter gap and therefore can be borrowed from laboratory measurements, where its relative value is close to 0.1. It is clear that the presence of an orientation standard determines the well-known fact of lightning striking the side surfaces of buildings and structures. This aspect is not taken into account by the standardized RSM method. However, this probability should not be taken into account for structures with a height of less than 60 m [3].

To design a lightning protection system, among other characteristics, it is important to estimate the expected number of strikes N_s for a certain period (usually 1 year) to the territory of the object and to determine the probabilistic statistical distributions of lightning strikes to its elements. It is clear that the number of hits depends on N_G and the collection area S_{at}. For isolated buildings (structures) on flat terrain, S_{at} is the area defined by the intersection between the ground surface and a straight line with an inclination of 1/3, which is tangent to the highest points of the building (structure) and which revolves around them [2]. Determining the size of S_{at} can be done graphically or mathematically. For the mathematical definition of S_{at}, the empirical formula (2) is given in the standard [2, formula A.2] for an isolated rectangular structure with length L, width W, and height H, located on a flat terrain:

$$S_{at} = L \cdot W + 6 \cdot H \cdot (L + W) + 9 \cdot \pi \cdot H^2\ . \qquad (2)$$

The use of (2) for real objects of critical infrastructure is difficult and not sufficiently reliable. The RSM method is based on the application of the lightning strike distance (R) to the structure or to the ground, which are related to the maximum value of the return current (I). The dependence of the R value on the current is determined by a number of formulas obtained by different authors for different variants of the current polarity and the shape of the structure based on experimental observations. A comparison of such formulas is given in

[14]. At this time, it is appropriate to apply formula (3) given in the standard [1]:

$$R = 10 \cdot I^{0.65}, \quad (3)$$

where R is the lightning strike distance, m; I is the maximum value of the lightning current, kA.

An important factor influencing the results of the assessments is the probability distribution of the maximum lightning current in the area where the object is located. Variants of statistical current distributions are differentiated depending on the height of structures, for positive or negative lightning polarity, obtained on supports and power lines or by remote methods in lightning detection networks. This should be taken into account when using statistical distributions. At this time, it is appropriate to use the dependencies that are summarized in the standard [1] and the CIGRE technical report [15]. It should be understood that research on the clarification of dependence continues [16]. However, changing the dependency will not affect the applicability of the proposed approach. The application of the concept of the RSM method allows to estimate the probability of lightning striking the elements of the object for any given lightning current. In [14], the calculation results for 5 shapes of buildings (cylinder, parallelepiped, hangar in the form of part of a cylindrical surface, round and rectangular houses with internal deflection) and three levels of probability of current (0.5 %, 50 % and 95 %) are given. The results show that the number of lightnings calculated by the RSM method is significantly different from the estimation by the standard approach [2], due to the use of the collection area.

Taking into account the probability distribution of lightning current in a given range of currents, with an arbitrary number of intervals, is proposed in [17-19].

The goal of the work is to substantiate the expediency of taking into account the statistical distribution of lightning current when determining the probability of lightning striking the elements of the object, and the effectiveness of using the improved «rolling sphere» method.

Research methods: the method of mathematical modeling, based on RSM with additional consideration of the probability distribution of lightning current.

Mathematical model of the process. The research object is the territory where the elements of the object (buildings and structures) are arbitrarily placed. With a certain step, a mesh is set on the surface of the earth. If mesh nodes are indexed by the value i on the X axis, and by the value j on the Y axis, then an arbitrary mesh node is denoted as (i, j). In fact, the mesh nodes determine the coordinates of the projection of the point from which the lightning strikes the object onto the horizontal plane. The density of mesh nodes should be set taking into account the size of the object's elements. For each mesh node, the maximum height at which the «rolling sphere» touches the surface of any structure is determined. It is clear that for the surface of the earth the height is zero. If there are several such points (let's denote their number as k), then, assuming that they will be struck with the same probability from the given center of the «rolling sphere», it is concluded that the number of lightning strikes of any of these points will be k times less.

The lightning orientation process is considered started when the radius R (discharge distance) reaches the surface of the object's element. Thus, the orientation distance of each lightning depends on the lightning current. This aspect significantly affects the determination of the probable collection area, and as a result, the probable number of lightning strikes to the object during the year. The proposed process model leads to important conclusions:

- the collection area is determined by the maximum current from the range taken into account;
- the lightnings with minimum current have probability of bypassing the system of lightning arresters.

It is obvious that such properties are not taken into account when using (2), and defined protection zones by the angle method. It is advisable to specify the geometric parameters of the object's elements directly in a specialized PC code without using additional elements of CAD software. Using the general plan of the object, the optimal mesh step is determined. Research experience [17-19] shows that arbitrary structures can be adequately specified using a combination of vertical wires and cables (horizontal or inclined). The distance between such structural elements must be consistent with the mesh step and be less than the minimum radius R of the current range under consideration.

Object points – points of fragments of structures and nodal points of the ground on the territory of the object for which the statistical characteristics of their strike by lightning with a given level of reverse current are determined in the course of the software operation. The discharge distance is determined by the given value of the lightning current by (3). The implementation of the calculation algorithm in the form of two specialized codes [20, 21] for a personal computer was performed by Docent of NTU «KhPI» V.M. Dronov. Codes [20, 21] assume that the law of lightning current distribution is described by the dependence under which the probability P that the peak value of the lightning current will exceed the value I is determined according to (4) [1]:

$$P(I) = \frac{1}{1+(I/a)^b}, \quad (4)$$

where P is the probability ($0 \le P \le 1$); I is the limit value of lightning current, kA; a and b are the non-negative parameters that, according to [1], have the following values: $a = 31$ kA, $b = 2.6$.

The values of parameters a and b can have the above default values, as well as other values at the request of the software user.

The results of the calculation estimation. As an example, consider the results of the application of the code [20] to estimate the predicted number of lightning strikes in the structure of the New Safe Confinement (NSC) of the 4th power unit of the Chornobyl NPP. The NSC has the shape of part of a cylindrical surface. In order to estimate the number of expected lightning discharges in the construction of the NSC, the following dimensions of the NSC should be adopted: width 256 m, length 163 m, height 110 m. The density of lightning discharges in the Chernobyl NPP area is taken as $N_G = 4.69$ discharges per 1 km^2 per year. The construction of the NSC is modeled by 75 horizontal cables located along the length with vertical descents, including:

- medium (along the crest);
- right and left on the ground;
- intermediate with a step of 3.4 m along the width.

The range of lightning current (2–200) kA is considered. According to [1, Table A.3] the probability that the lightning current will exceed the specified range is no more than 2 %. The results of the calculations are presented in the Table 1.

Table 1

The results of the calculation estimation

Current range, kA	Probability of a strike in the NSC	Number of hits per year	Mesh step, m
2 – 200	0.2478	1.162	2.5
2 – 200	0.2481	1.164	0.31

Note: The calculations were made for two versions of the calculation mesh step, which differ from each other by 8 times. The results of both cases differ by less than 0.2 %.

The code [20], in addition to the integral value, allows to determine the distribution of the probability of lightning strikes by individual elements. As an example Fig. 1 shows a screenshot of the probability distribution over the ground around the NSC. Such information is also useful for rational placement of additional NPP equipment.

It should be noted that the determination of the relative probability of the strike is carried out for each object separately (in this case, it is the NSC and the ground). Therefore, the maximum values (marked in red – 1) are found both on the shelter and on the ground far from the shelter. As you approach the NSC, the probability decreases, because part of the lightning with a large current is oriented to the NSC.

According to the results of the calculation estimation, it was determined that the predicted number of lightning discharges in the NSC structure is 1.16 per year. Therefore, for 100 years of operation, the number of lightning strikes in the NSC will be 116. The error of the estimation is within 3 %.

We compare with the results of the calculation according to the standardized method [2]. The collection area is determined by (2). After substituting the NSC parameters, the obtained value of S_{at} = 0.66 km^2 per year. Taking into account the average density of N_G = 4.69 discharges/(year·km^2), the number of lightning strikes in the NSC is estimated at 3.095 per year. Therefore, 310 lightning strikes may occur within 100 years, which is 2.67 times more than the number of strikes calculated according to the refined methodology.

The reasons for the difference are determined by the following circumstances:

- the standardized method does not take into account the real shape of the NSC, different from a parallelepiped;
- the standardized method does not take into account the statistical distribution of the lightning current;
- the standardized method is based on the results of experimental studies obtained mainly for mast or rod type objects.

It should be noted that the presence of a significant difference between the results of estimating the number of lightning strikes in the NSC using a standardized method and a method that takes into account statistical distribution is also indicated in [14].

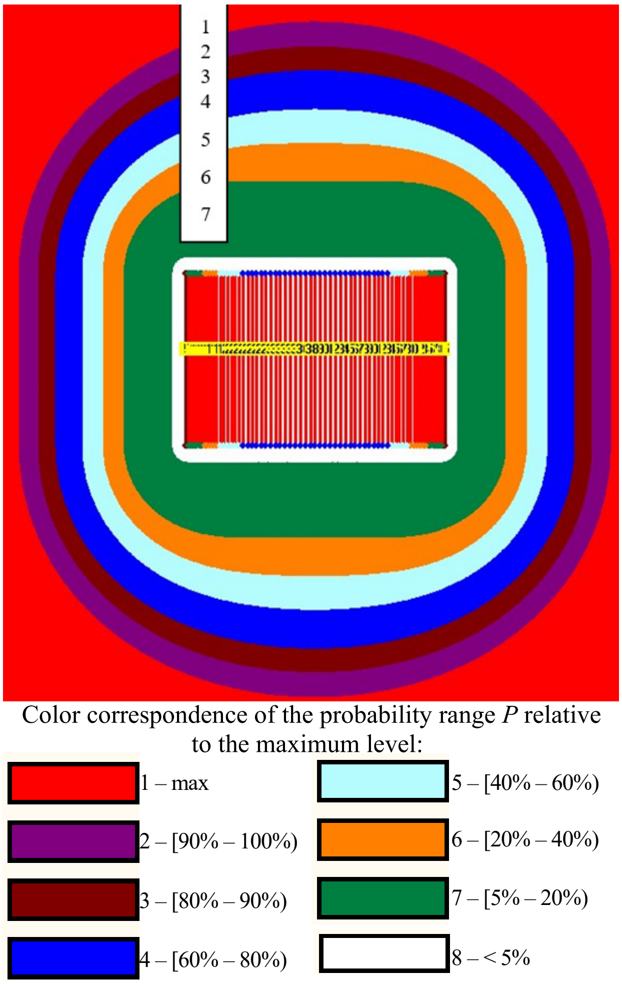

Fig. 1. Distribution of the probability of a lightning strike on the ground around the NSC

Let's consider the features of the calculation model of the code [21] for determining the collection area. For the purpose of simplification and clarity, as a model we will consider the most common variant of a lightning arrester – a mast with a height of h. The code takes into account that for the mast h and the lightning current, which corresponds to the lightning breakdown radius r, the radius of the collection area R_{at} is determined as:

$$\begin{aligned} R_{at} &= r, \;\; r \le h, \\ R_{at} &= \sqrt{h\cdot(2r-h)}, \;\; r > h. \end{aligned} \qquad (5)$$

It follows from (5), if $r \ge 5h$, R_{at} is proportional to $h^{0.5}$. Thus, the collection area is proportional to h, not h^2, as defined in (2), in which $H \equiv h$. For the option when $r \le h$, the collection area approaches the proportionality to r^2, and does not depend on the height h, that also differs from the empirical formula (2). It is known that (2) is based on the results of experimental studies under most laboratory conditions, in which the height of the rod was proportional to the length of the breakdown gap ($R_{at} \approx h$). The author assumes that this very fact caused the appearance of formula (2).

Appropriate formulas for cables, both horizontal and inclined, parallelepipeds, cylinders, etc., were defined [19]. For a rectangular structure, the collection area is calculated as:

$$S_{at} = \pi \cdot R^2 + L \cdot W + 2R(L + W), \quad (6)$$

where R is the radius of the collection area of the mast of the same height as the height of the building H. The value of R is determined by (5); other notations are the same as (2).

Another aspect, from the point of view of the developed approach, is that the values of the lightning currents are stochastic in nature. Each of these random values corresponds to its lightning breakdown radius value and defines the collection area. Thus, it is necessary to talk about the value of the area S_{at} as a random value, and therefore it is advisable to calculate the average value of the collection area for a specific composition of buildings. Then, knowing the dependence of the values of S_{at} for a specific structure with the specified parameters of its geometry on the radius of the lightning breakdown, and therefore, according to (3), on the value of the lightning current, it is possible to determine the average value of the collection area S_m:

$$S_m = \int_{2}^{200} S(I) F(I) \mathrm{d}I, \quad (7)$$

where the lower and upper values determine the current range under consideration; $S(I)$ is the object's collection area for a given value of the lightning current; $F(I)$ is the function of the density of lightning current values, which is defined as:

$$F(I) = \frac{b \cdot a^b \cdot I^b}{I \cdot \left(a^b + I^b\right)^2}, \quad (8)$$

where a and b are defined in (4).

The code uses a simplified formula:

$$S_m = \sum_{i=1}^{n} \left(S_i F_i\right), \quad (9)$$

where n is the number of numerical integration intervals; S_i is the value of the desired characteristic when the lightning current is equal to the average value of the current within the i-th integration interval; F_i is the probability that the value of the lightning current will be within the i-th integration interval.

The results of the comparison of two methods of estimating the collection area for masts of different heights are given in Table 2. Calculations of S_m are made for the range of current from 2 kA to 200 kA. Calculation according to (2) does not take this range into account.

Table 2

Comparison of the results of the collection area calculation by RSM and standard [2]

Height h, m	Current range, kA	Area S_m, km^2	S_{at}, km^2	S_{at} / S_m
20	2-100	0.012	0.011	0.92
40	2-100	0.020	0.045	2.25
60	2-100	0.027	0.102	3.78
80	2-200	0.031	0.181	5.86

Note: S_{at} is calculated by (2) for a mast of height h.

The results given in Table 2 unequivocally indicate a significant overestimation of the value of the collection area of lightning, as a result of which the result of estimating the number of hits to the object has overestimated values. From the point of view of risk assessment, this fact is unacceptable.

Conclusions.

1. The expediency of taking into account the statistical distribution of the lightning current at the determination of probability of lightning striking the elements of the object, which is determined by the dependence of the breakdown distance of the air gap between lightning and the object on the potential of the head of the lightning leader, which is related to the lightning current, has been proven. Increasing the reliability of estimating the number of strikes on an object affects the quality of decision-making regarding the risks associated with the consequences of a lightning strike.
2. The effectiveness of the improved «rolling sphere» method, implemented in the form of a computer code, which takes into account the given probability distribution of lightning current in the range from 2 kA to 200 kA, has been proven. Setting the real configuration of the object elements is provided by a combination of vertical wires and cables.
3. The expediency of introducing the concept of «average value of the collection area» is substantiated taking into account the probability of lightning with current in a given range, for example 2 – 200 kA. Examples of the difference of the obtained results from the evaluation according to standardized formulas in the direction of decreasing probability are given. For a hangar-type object with dimensions: width 256 m, length 163 m, height 110 m, the probability of lightning strikes is 2.67 times lower.
4. It has been established that the application of the standardized formula leads to a significant (many times) overestimation of the predicted number of lightning strikes to the object, if the height of the object exceeds 20 m. The reasons for the difference, according to the author, are due to the following properties of the standardized methodology:

- usually, the real shape of the object is not taken into account;
- statistical distribution of lightning current is not taken into account;
- it is based on the results of experimental studies obtained mainly for objects of the mast or rod type in laboratory conditions with a limited discharge gap.

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