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Statistical Analysis for Probable Varying Potential Lightnings Strokes to Extended Objects

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Abstract: In the paper, the statistical modeling method of the lightning attachment process to extended objects has been proposed. The modeling takes into account the probabilities of lightning occurrence with current of different amplitudes, and nonlinear variation of spark resistance at leader channel growth. The method also takes into consideration the dependency of velocity and acceleration of a lightning leader on its potential. The propagation of lightning channel towards the earth is tortuous and random in orientation and does not depend upon ground objects until it enters into "last stroke zone". It assumes that the lightning leader channel orientation begins when its streamer zone touches the earth, a grounded object, a grounded lightning rod or a streamer zone of the ascending leader. The probable frequency of lightning strikes to an investigated object can be obtained by the summation of the total probable number of strikes of all possible potentials at each node of the object, appearing with the assigned probability, as well as the points of origin of the heads of lightning leaders from all nodes on the plain (over the object) at corresponding heights. The proposed method is implemented to calculate the lightning stroke probability to a high voltage substation. Due to lightning attraction from the territory greater than that of the investigated object, the total number of annual probable lightning strokes to the object is increased by 1.28 times in comparison with the case of the same flat territory.

Key words: Lightning; Extended objects; Statistical modeling; Probability; Potential; Velocity; Acceleration; Lightning leader
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0 Introduction

A successful risk assessment methodology maintains specific protocols for determining and mitigating the risk of damage due to lightning. Generally, statistical modeling methods of the lightning attachment process demonstrate the approximate number of lightning strokes over a given period of time. This data can then determine the degree of protection necessary for a given facility and whether the current systems are robust enough to help allay disaster. According to operating standards[1], calculation of the expected number of lightning strokes to buildings and installations are done under the assumption that equivalent collective area of a structure (A_e) depends on its height (H), and for a rectangular structure with dimensions LW(L, Length; W, width) should be calculated as $A_e = LW + 6H(L+W) + \pi 9H^2$. Thus, the operating standards do not consider the possibility of lightning attachment with high potential U_L (potential of lightning leader head) when lightning strikes from the distance greater than $3H$.

There exist a number of models, which describe lightning channel movement to the earth[2-3]. However, these models do not consider all relevant factors that affect the downward propagation of lightning channel. These factors include dependence of velocity and acceleration of the lightning leader head on its potential, nonlinear variation of spark resistance in the process of leader channel growth, and grounding system resistance.

The purpose of the work is to elaborate the method, which corresponds to the estimation of lightning attachment probability to extended objects. The method assumes that the lightning leader channel orientation begins when its streamer zone touches the earth, a grounded object, a grounded lightning rod or a streamer zone of the ascending leader[4-5].

1 Main Features and Assumptions of the Proposed Method

The model is based on generalization of the experimental results of impulse voltage breakdown of "rod-plane" long gaps (about 30 m)[6]. In the experiment, two main stages of the breakdown process are considered. The first stage begins with the appearance of corona and the streamer zone reaches the opposite electrode at the last stage. During the reduction of streamer zone length, there is a decrease in the streamer's specific resistance, which is still in many orders greater than that of the leader. The specific resistance of the discharge channel during the final stage is a transition between the leader and the streamer channel specific resistance. According to the experimental results[6], the average specific resistance value of streamer channel in the last stage is approximately

10^4 Ω/m.

For the electric field strength of positive leaders, which is not less than $E_L^+ = 5$ kV/cm, and for negative leaders, which is not less than $E_L = 10$ kV/cm, the control mechanism of lightning leader movement by weak external electric field ($E_0 \approx 100$ V/cm) is explained in[6] as follows. A velocity of a leader is defined by potential difference between the lightning leader head (U_L) and the exterior field potential (U_0). The big difference, $\Delta U = |U_L - U_0| \approx 10 \sim 100$ MV, in a short length of a streamer zone creates necessary field, $E_L \approx 5 \sim 10$ kV/cm $\gg E_0$, for streamers formation and leaders propagation. It is supposed in[6], that the strength of external field assigns leader's acceleration. It is also supposed that velocity of a leader is a function of the absolute value of potential difference between the leader's head and the external field: $v_L = f(\Delta U)$. The empirical formulas relating the velocity (v_L) and acceleration of a lightning leader (dv_L/dt) with the potential difference gradient acting on its head may be written as follows[6]:

$$v_L \propto \sqrt{U_L};\frac{dv_L}{dt} = 0.5\frac{v_L}{\Delta U}\left(-\frac{dU_L}{dt} - \boldsymbol{E}_0 \boldsymbol{v}_L\right). \quad (1)$$

The last stage of a lightning leader channel movement to the earth or grounded objects begins when they are reached by the streamer zone of the lightning channel. It can be stated that the "last stroke" is a process of leader channel movement through the streamer zone. As an example, let us consider negative polarity lightning strikes as they are more common. At propagation of a negative leader, the minimum level of the electric field strength in the streamer zone is approximately equal to $E_L = 10$ kV/cm and height of the orientation zone may be written as:

$$L_{st0} \approx U_L/E_L^-. \quad (2)$$

In the case of positive lightning strike, E_L^- should substitute E_L^- in (2). For a lightning leader with a potential of $U_L = -10 \sim 100$ MV, the height of the orientation zone is expected to be about $20 \sim 100$ m. This approximately matches with the data from[7].

The equation for current flowing through a grounded object and earth section to which a streamer has been connected after beginning of the last stroke may be written as:

$$i_F = U_L/(\rho_F L_{st} + R_R + R_G), \quad (3)$$

where, i_F is the discharge current in the last phase; ρ_F is the resistance per streamers' channel length in the last stroke phase; R_R is the resistance of the over-ground part of the object; L_{st} is the length of the decreasing streamer zone; R_G is the dissipation resistance of the grounding system.

It is noticed in [6] that during the last stroke phase of development of a leader in a long air gap, there is intense branching of discharge channels, and several parallel branches may appear simultaneously. During the final stage of lightning movement to a grounded object or towards the earth, simultaneous development of several competing streamers is observed. However, a return stroke will happen only through the one that reaches the point of zero potential first. Mutual influence of streamers' electric field may be disregarded considering the fact that the diameter of streamers' channels is much less than their respective length and corresponding distance between them.

It is known that the process of lightning leader movement in the ionized streamer zone possesses a stochastic character. Therefore, all possible directions of leader propagation from various distances and heights should be considered successively. A leader may have various initial propagation velocity: $v_L = 10^5 \sim 10^6$ m/s[6]. Quantities of v_L and L_{st} are correlated with the voltage level of a head of leader U_L, so these parameters are dependent upon each other (see (1), (2)).

Let us consider that in the last stroke phase, the head of a lightning leader is terminated with a grounded point. The grounded point denotes a streamer zone with resistance $R_F = \rho_F L_{st}$. To define the discharge current through the streamer zone, the relationship of streamer zone resistance ρ_F (resistance per streamers' channel length in the last stroke phase) and L_{st} (length of the decreasing streamer zone) has been considered.

As the discharge current through the streamer zone rises to several kilo amperes and more, the streamer channels begin to widen. With the widening of streamer channels, the streamer zone resistance begins reducing. The relationship of streamer zone resistance $\rho_F(i_F, t)$ may be expressed as an empirical formula[8]

$$\rho_F(i_F, t) = 1/\left(k_b \int_0^t i_F^{2/3} dt\right), \quad (4)$$

where, $k_b = (r\pi\sigma^2/\rho_0\xi)^{1/3}$; ρ_0 is the density of gas in which discharge takes place; σ is the specific conductivity of the discharge channel (3×10^2 S/cm for air), and coefficient $\xi = 4.5$.

Let us assume that a considered grounded point will be struck by lightning when the leader reaches it or the resistance of the successful streamer channel has fallen to a level defined as below

$$\rho_F = k_F \rho_L. \quad (5)$$

where, $\rho_F = 10$ Ω/m is resistance per leader channel length; $k_F = 10$ is a coefficient.

Let us further assume that the fulfillment of the last equation is a requirement for a streamer's transformation into a leader. A streamer is characterized by low conductivity and hence shall not readily become a leader.

The principle analogous to "Least Time-Maximum Probability"[9] is used to describe a lightning leader selection process of an object that is being struck. It is considered that the probability of a lightning leader attachment to a grounded object is inversely proportional to the time of that leader approaching the object.

The algorithm below describes how to define the duration of k-th leader's channel movement at assigned level of L_R, the distance of the grounded object to the head of the considered leader and U_L, the potential gradient acting on the leader's head. The value of U_L defines the values of L_{st} and v_L (see (1), (2)). As a result, the full time necessary for leader connection to i-th grounded object is calculated.

2 Algorithm of Probable Lightning Attachment Distribution Process to an Extended Objects

It is important to calculate the probability of lightning strikes and assess the lightning protection system reliability for facilities (such as power substations, oil & gas transfer stations, etc.) under design or for those already existing.

Besides calculation of the probability of lightning strikes, obtaining information for the possible values of voltage and current that the strike may carry can also be helpful. Software has been developed to calculate the required information. The basic input data comprises of the evaluated facility's geographical coordinates, elevation of each component on the facility, location and height of lightning air terminal and shield wires.

The proposed algorithm considers all possibilities of lightning strike origination from different nodes on the calculated domain. The algorithm calculates movement time of streamer to each zone of the object under evaluation. The algorithm takes into account the possible range of lightning leader channel potentials.

The algorithm assumes that the lightning leader will strike only those points for which the expected time to reach does not exceed $1.1\times t_{\min}$, where $t_{\min}$ is the minimum time of lightning leader propagation to a grounded spot considered in this experiment. This 10% dispersion corresponds to the values of probable discharge times and voltages of multi - meter air gaps with sharp non - uniform electric field[6]. Probability of stroke in k-th mesh of an investigated object by a lightning with potential U_i, leader of which originates in j-th node of the calculated domain is defined as P^*_{kij}. The equation for P^*_{kij} may be written as follows

$$P^*_{kij} = N_{kij}/N_{ij}. \qquad (6)$$

where, $N_{kij}=1$, if k-th node may be struck by lightning in the considered numerical experiment, $N_{kij}=0$, if not; N_{ij} is the total probable number of lightning strikes at all possible nodes for the considered numerical experiment.

If the probability of occurrence of lightning with currents smaller than I_i, i. e. $P(I_i)$[10], is known, and N_{kij} is the sum of all strokes of lightning, which leaders originate from the j-th nodes of the calculated domain, the expression for the probable frequency of lightning strokes to k-th mesh with the dimensions $\Delta\times\Delta$ may be written as follows

$$P_k = \sum_{i=1}^{M}(P_{\Delta i}\sum_{j=1}^{I}\Delta^2 N_{kij}/N_{ij}), \qquad (7)$$

where, M is the number of intervals into which the range of lightning current variation is divided;

$$\sum_{i=1}^{M}P_{\Delta i} = 1;\ P_{\Delta i} = P(I_{i+1}) - P(I_i). \qquad (8)$$

The probable annual lightning strike frequency at the k-th mesh (with dimensions $\Delta m\times\Delta m$) of the grounded object may be defined as

$$N_k = P_k 10^{-6} N_m, \qquad (9)$$

where, N_m is the annual average flash density per square kilometer in the region where the investigated object is located[1].

Level of the coefficient ($P^*_k = P_k/\Delta^2$) shows the probable frequency of lightning strikes to a grounded cell relative to the annual average flash density of the region. Thus, it is expected that the coefficient for lightning rods will be $P^*_k \gg 1$, as they are expected to attract lightning from a substantial number of nodes on the "Calculated Domain"; for the objects which are located in the zone of protection of lightning rods the expected coefficient value is $P^*_k < 1$; and for flat areas the expected coefficient is $P^*_k = 1$.

To predict the number of lightning strokes, the probability range of negative lightning with a current falling into the interval ($I_{i+1} - I_i$) was partitioned into 21 parts. A functional relation between lightning leader potential U_1 and lightning current I_1 can be determined in accordance with [6] is taken to be

$$U_l \approx (500/0.6)\cdot I_1 \qquad (10)$$

This relationship can also be determined with the formula from[11] relating last stroke distance R and lightning current I_1 in the first component, $R=9.4I_1^{2/3}$, where R is in meters, I_1 is in kA. Then, we have

$$U_l = E_L^- \cdot R$$

where, U_1 is in MVs, E^*_L (in MV/m) is the field strength necessary for a leader of negative polarity to advance.

It is commonly accepted that the mean length at which the negative lightning leader begins orientation is taken to be equal to 30 m, which corresponds to a typical lightning current of 30 kA, indicates that the relationship between the lightning current and lightning potential derived in [6] (see Table 1) is more reliable than that given in [11]. The value 30 m is obtained if one uses the dependence $U_1(I_1)$ given in [6] rather than in [11].

Tab. 1 Probability of occurance of lightning with different currents and potentials

I_l/kA	$P_{i+1}-P_i$	ΔP_i	U_l/MV
2～3	1～0.99	0.01	8
3～4	0.99～0.98	0.01	8.5
4～5	0.98～0.97	0.01	9
5～6	0.97～0.96	0.01	10
6～7	0.96～0.95	0.01	10.5
7～8	0.95～0.93	0.02	11
8～9	0.93～0.92	0.01	11.5
9～10	0.92～0.91	0.01	12.5
10～12	0.91～0.89	0.02	12.5
12～15	0.89～0.85	0.04	13
15～20	0.85～0.79	0.06	14
20～25	0.79～0.72	0.07	18
25～30	0.72～0.57	0.15	22
30～40	0.57～0.37	0.2	28
40～50	0.37～0.25	0.12	36
50～60	0.25～0.15	0.1	44
60～70	0.15～0.08	0.07	52
70～80	0.08～0.05	0.03	60
80～90	0.05～0.03	0.02	70
90～100	0.03～0.02	0.01	75
100～150	0.02～0.000	0.02	100

The algorithm of the program is the following. The investigated object is covered by a square grid with assigned spatial step Δ. The same grid is applied on a plane above the object (let it be called the "Calculated Domain") from which lightning may strike any of the object's meshes. Since a lightning stroke may come from a zone outside the territory of interest, the "Calculated Domain" is larger than the region occupied by the object. All possible scenarios of lightning stroke from each of the meshes in the "Calculated Domain" are considered. To do this, we fix the location of the lightning leader top in a certain mesh of the "Calculated Domain" and calculate the time it takes for a spark in the streamer zone of the lightning leader channel to reach each of the meshes of the object. At this, the lightning leader channel potential is found by formula (10) for a certain lightning current at assigned probability of lightning appearance (see Table I). The module of the program that simulates the advance of the lightning leader channel in the streamer zone takes into account the nonlinear variation of the spark current, dependence of the acceleration and velocity of the streamer on the electric field strength, spreading resistance at the site the spark meets the ground, and other factors[5]. The height from which the lightning leader channel starts orienting is defined as a minimum height from which the top of the leader channel of a lightning with potential U_i relative to the ground or grounded area reaches a distance equal to the radius of the negative streamer zone, $L_{\mathrm{st}}=U_i/E_{\mathrm{L}}^{-}$. We will assume that lightning strikes only those meshes of the object which are reached by it for a time period not exceeding 10% of the minimum time for a given numerical experiment[4]. Having summed the predicted number of strokes to each mesh of the object by running over all possible potentials of the lightning leader channel that arise with a definite probability[10] and over all locations of the meshes in the "Calculated Domain", we obtain the distribution of the number of strokes over the territory of the object.

To validate the proposed method, the probability of lightning stroke to an extended object located wholly within a zone is calculated which provides its protection with 95% reliability. To show the difference between the predicted numbers of lightning strokes to lightning air terminals of various heights and to objects protected by them, we estimate the number of lightning strokes to three geometrically similar air terminal-object systems. Let a system to be protected have the form of a parallelepiped (building) of height H occupying surface area $D\times D$ and a lightning air terminal located at the center of the upper base (roof) with height h. The total height of the lightning air terminal $(H+h)$ is chosen such that the protected object is located within the protection zone providing a reliability level of 95% according to [12].

Analyzing the data obtained from the performed calculations, some conclusions can be made. First, although the ratio between the number of predicted lightning strokes to local regions of the protected zone and strokes to the lightning air terminal in all cases is approximately the same and does not exceed 0.05, i. e., a reliability of 95% declared in [12] is provided, the absolute levels of predicted number of strokes became higher with augmentation of the system's overall dimensions.

3 Example of Lightning Attachment Probability Calculation to a High Voltage Substation

An example for calculation of the lightning stroke probability to an investigated object (a high voltage substation) is illustrated below. The facility is comprised of 6 buildings with the length and width as plotted in Fig. 1. The height of buildings 1 to 6 are $H_1=24$ m; $H_2=4$ m; $H_3=24$ m; $H_4=4$ m; $H_5=4$ m; $H_6=4$ m. The facility has installed lightning protection terminals of $H_7=55$ m; $H_8=30$ m; $H_9=34$ m; $H_{10}=34$ m and H_{11} is a lightning protective mesh with grid of 54 m^2 at 2.5 m above the building 1.

Fig. 2 to Fig. 5 illustrate distribution of coefficient P^* proportional to the probability of lightning attachment, calculated as $P^*=P_{\mathrm{k}}/S_{\Sigma}P_{\mathrm{k}}$ is the probable frequency of lightning strokes to k-th node (see (7)); S_{Σ} is the area of an investigated object which is $S_{\Sigma}=150\ \mathrm{m}\times 120\ \mathrm{m}$ for the illustrated example (Fig. 1). Fig. 2 presents probability of lightning strikes with $U_{\mathrm{L}}=-8$ MV ($P_{\Delta i}=0.01\%$, see (8)); Fig. 3 corresponds to probability of lightning strikes with $U_{\mathrm{L}}=-22$ MV ($P_{\Delta i}=0.15\%$); Fig. 4 presents probability of lightning strikes with $U_{\mathrm{L}}=-100$ MV ($P_{\Delta i}=0.02\%$). The distribution of calculated coefficient P^* for the full range of probable lightning strike potential (from -8 MV to -100 MV) is illustrated in Fig. 5. Analysis of plots in Fig. 2 to Fig. 5 shows that the probability of lightning attachment is dependent on the value of the potential gradient acting on the leader's header. N^*_{obn}, the predicted number of all lightning strikes to n-th object in the example, and N^*_{on}, given by S_n/S_{Σ} (where S_n is area of n-th object), are presented in Table 2. With this, the total annual probability of lightning strikes to the objects is defined as $N_{\mathrm{k}}=N^*_{\mathrm{obn}}S_{\Sigma}\cdot 10^{-6}N_{\mathrm{m}}$ (see (9)). The numbers of objects N correspond to the plan shown in Fig. 1.

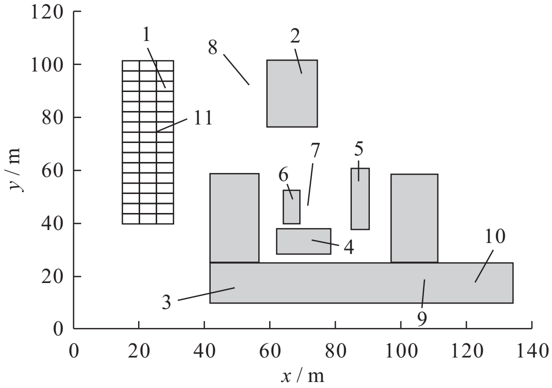

Fig. 1 Plan of the investigated object

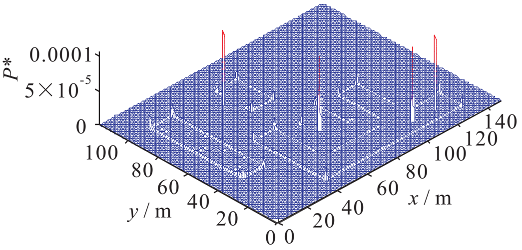

Fig. 2 Probability of lightning strikes with $U_{\mathrm{L}}=-8$ MV($P_{\Delta I}=0.01\%$)

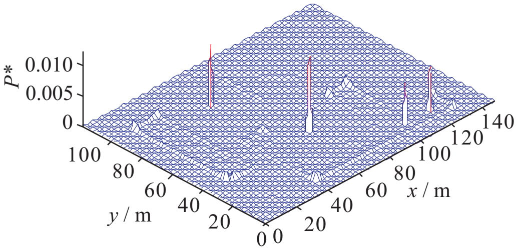

Fig. 3 Probability of lightning strikes with $U_{\mathrm{L}}=-22$ MV($P_{\Delta I}=0.15\%$)

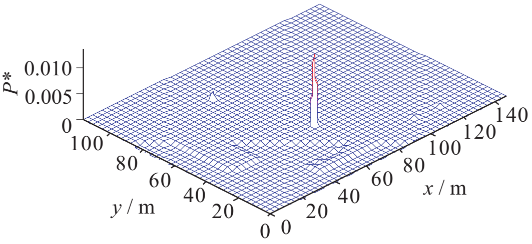

Fig. 4 Probability of lightning strikes with $U_{\mathrm{L}}=-100$ MV($P_{\Delta I}=0.02\%$)

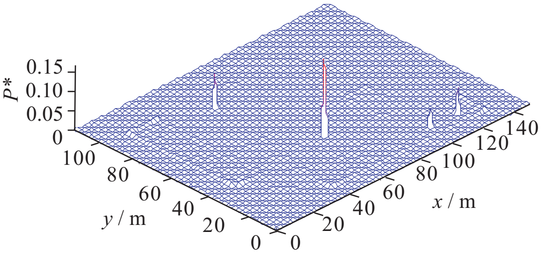

Fig. 5 Probability of lightning strikes with $U_{\mathrm{L}}=-8\sim 100$ MV

Tab. 2 Predicted number of strikes to the objects

N	1	2	3	4	5	6	7	8	9	10	11	Ground
N^*_{obn}	0.015	0.02	0.389	0.0003	0.0034	0.00076	0.17	0.079	0.042	0.059	0.295	0.205
N^*_{on}	0.05	0.02	0.133	0.009	0.008	0.002	~0	~0	~0	~0	0.0003	0.778

4 Conclusion

In the paper, a technique for numerically predicting the distribution of the number of lightning strokes to extended objects protected by lightning air terminals is developed. The technique takes into account the probability of lightning with various potentials. It is supposed that the time instant the streamer zone touches a ground area or grounded object is the time instant the lightning starts orientating toward them. The technique also considers the nonlinear variation of the spark current in the streamer zone, field dependence of the velocity and acceleration on the streamer, and influence of the dissipation resistance of the grounding system.

An example of calculated probable lightning strikes distribution in the territory of a high voltage substation has been performed. Due to lightning attraction from the greater territory than of the investigated object, as it follows from the Table II, we have, i. e. the total number of annual probable lightning strokes to the object is increased by 1. 28 times in comparison with the case of the same flat territory, i. e. .

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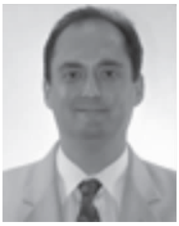

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