УДК 621.316.98

PHYSICAL MODELING OF ELECTRICAL PHYSICAL PROCESSES AT LONG AIR GAPS BREAKDOWN

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The results of physical modeling of the influence of corona discharge intensity at the grounded objects tips on the probability of their strokes by high-voltage discharges in the long air gaps "high voltage rod –rod on the grounded plane" are presented. The system consisting of a vertical high-voltage negative electrode rod, simulating the lightning channel leader, and two grounded rods, simulating lightning rods (one with a spherical and the second with a pointed tip) has been investigated. Before application of the high voltage impulse up to 1 MV to the high-voltage electrode, the pre-breakdown DC electric field (EF) was applied to the electrode system. The experiments have shown that corona presence at the pointed electrode tip increases probability of being struck by high-voltage discharges at application of the DC electrical field strength, which is of the same order as the impulse EF strength.

References 11, figures 2, tables 2.

Key words: physical modeling, electrical physical processes, the probability of hitting by high-voltage discharges, corona current, lightning.

Introduction. At choosing of the lightning protection means, it is important to evaluate the probability of lightning attachment to lightning rods and protected objects. Direct measurement of the electrical parameters of such objects as the leader of lightning channel is practically impossible, so physical and mathematical modelings of the electrical physical processes that accompany lightning discharges are widely used [1, 2, 6-8].

It is known that the upward leaders may develop from the grounded objects to the lightning leader channel in a storm situation [2]. This is connected mainly with the fact that most lightning in the mid latitudes have a negative polarity [1, 2]. The average electric field (EF), necessary for development of the leader channel of a positive polarity (E_+) is equal to: $E_+\approx 5$ kV/cm, which is about two times less than the average EF stress needed for development of the leader channel of a negative polarity ($E_-\approx 10$ kV/cm) [2]. The presence of EF caused by propagation of the lightning leader channel of a negative polarity can cause development of an upward leader of a positive polarity from the grounded object.

The stage of streamer corona appearance and development precedes the stage of leader development at breakdown in the long air gaps [1, 2]. There are literary sources, which describe the simulation of spark process, arising at high speed of the discharge current [2, 9], at local electric field amplification [10] and the experimental study of the corona current dependence on the DC EF stress levels, as well as on the tip forms of the grounded rod electrodes, simulating lightning rods [3] (some electrodes were coated with erosion-resistant nanopowders [11]). However, the problem of investigation of the influence of corona intensity at the grounded electrode's tip on the probability of being hit by high-voltage discharges was not put. According to some literature data (see. e.g. [2]), the presence of a corona at the grounded electrode tip reduces the probability of development from it an upward leader.

The aim of this work is to study the influence of the corona current value, depending on the applied DC EF stress level as well as the form of the grounded electrode tip, on the probability of its hit by high-voltage discharges. Physical modeling of the electromagnetic processes in the vicinity of a lightning arrester, imitating the so-called "last stroke" phase [1, 2] was done with the help of a high voltage setup. This setup allows application to a discharge gap the megavolt voltage impulses, imitating approach of a negative lightning leader to a grounded lightning rod, located in the DC electric field, which simulates the electric field of a thunderstorm cloud in a storm situation. Two main cases are considered: the first, when discharges occur on the front of the applied voltage impulse (the EF strength intensity is much bigger than necessary for breakdowns), and the second when discharges occur on the tail of the impulse (the EF strength intensity is close to the minimal necessary for breakdowns). Three types of the grounded electrodes tips were considered: pointed (cone-shaped), from which corona discharges develops in all cases and two tips in the form of a sphere. The diameters of these spheres were chosen from the following. The first sphere diameter was chosen relatively large (0.125 m), so that corona discharges do not develop in any of the considered cases. For the second sphere having a smaller diameter (0.045 m), the corona intensity was significantly less than for the electrode with a pointed tip.

Simulation of the corona development electromagnetic processes on rod electrodes with the tips of different shapes. A high voltage setup (see Fig. 1) was used for physical modeling of the processes of hitting by a high-voltage discharge of the grounded rod electrodes, simulating lightning arrestors and defended objects. The Marx generator GIN-2.4 with stored energy up to W_{max}=3.6 kJ, 12 steps which form the discharge capacity C=7.1 nF was used as a source of high voltage impulses. Fig. 1 presents a physical model for investigation of the corona current influence on the breakdown processes (*1* is grounded plane; *2* is plane at U_{DC} potential; *3* are grounded electrodes, imitating lightning arrestors and defended objects; *4* is opening in plane *2*; *5* are tips of the grounded electrodes *3*; *6* is high-voltage electrode, h is height of the grounded electrodes; H is distance between the tip of electrode *6* and plane *1*; d is distance between the tips of electrodes *3* and *6*; D is distance between electrodes *1* and *2*, R is radius of curvature of one of the grounded electrodes tip). DC high voltage of a negative polarity U_{DC} of the level up to -200 kV was applied from the output of a DC voltage source to conductive plane *2* having dimensions 3×3 m. Corners, edges and elements of the setup were covered by the anti coronal screens with radii of curvature of not less than 100 mm. Plane *2* was suspended at a height D=2.1 m above grounded plane *3*, both planes are made from aluminum. The DC electric field between the suspended and the grounded planes imitates the conditions of lightning storm in which corona discharges can occur at the grounded electrodes tips. The average DC electric field stress is approximately equal to $E_0=U_{DC}/D$. With a sufficient level of DC EF stress, corona discharges appear at the tips *5* of the grounded rods *3* with height h located on the grounded plane *1*. The intensity of such discharges is characterized by the of the measured average corona current values (I_{cor}).

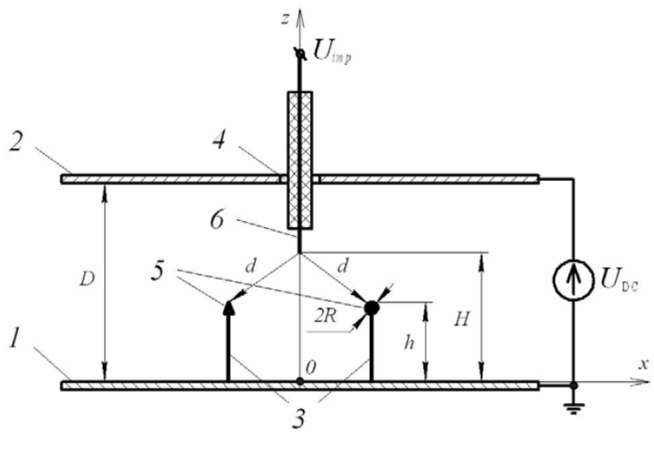

Fig. 1

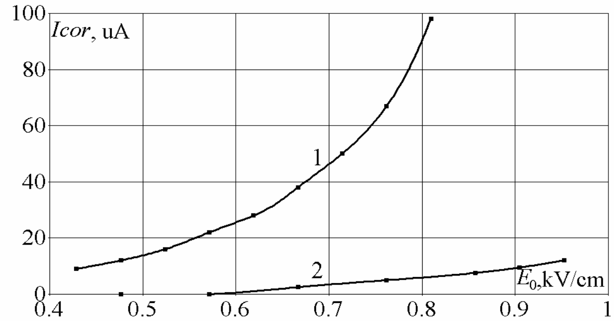

Fig. 2

Fig. 2 shows dependences of I_{cor} measured levels on the average DC EF strength levels (E_0) applied to the air gap between grounded (1) and potential (2) planes at the height of the grounded electrodes 3 h=1.2 m. Curve *1* corresponds to the case of corona current through the grounded electrode having a tip in the form of a cone with a height of 0.14 m and a base with a diameter 0.04 m. Curve *2* corresponds to the case of the grounded electrode having a tip in the form of a sphere with a diameter 0.045 m. As carried measurements have shown, corona current through the grounded electrode having the tip in the form of a sphere with a diameter 0.125 m for the considered electrode system is close to zero at h≤1.2 m and U_{DC}≤200 kV.

Modeling of the processes of high-voltage breakdown in the system with rod electrodes. High voltage impulse generator GIN-2.4, which was used for simulation of the processes occurring at approach of the lightning leader channel to the ground, provides voltage pulses of a negative polarity with the amplitude (U_{imp}) up to 1 MV, having 1.2 μs front and the impulse duration on the level of $0.5 \cdot U_{imp}$ equal to 50 μs.

High voltage was applied to electrode 6, the tip of which was at the distance d from the tips of the grounded electrodes *3* (see Fig. 1). High voltage electrode *6* passes through hole *4* in the suspended plane *2*, to which DC voltage U_{DC} is applied (see Fig. 1). The dimensions of this hole are chosen equal to 60X60 mm in order to avoid breakdowns between potential plane *2* and high voltage electrode *6*. As corona current measurements have shown, at location of the grounded electrodes on the distances in a diapason 0.7 - 0.14 m from the edge of the hole in the direction of the O*x* axis (see Fig. 1), the hole presence causes negligible effect on the corona current values.

The influence of the processes of corona pre-breakdown formation intensity on the probability of hitting the grounded electrode by a negative polarity leader was investigated in the carried experiments. For this purpose, the following scheme was used in all experiments. DC negative voltage U_{DC} was applied to potential plane *2*, several minutes prior to impulse voltage U_{imp} application on high voltage electrode *6* and up to breakdown of the air gap. So, all experiments were carried out at prior DC EF application and than at the combined impulse and DC voltages action. U_{DC} module was varied from 0 to 200 kV. At the experiments, the number of breakdowns to the grounded electrode with a pointed (cone) tip (N_P) and with a rounded tip (N_R) was recorded. If a high-voltage discharge struck both electrodes simultaneously, both values of N_P and N_R were increased by one.

Table 1 shows the results of experimental investigations carried out at the following parameters: the amplitude of impulse voltage $|U_{imp}|$=0.75 MV; h=1.2 m; d=0.44 m. The following notations are used: Nex_k is the number of experiments in k-th series; $P=N_P/N_R$ is relative frequency of high-voltage discharges hitting the grounded electrode having the tip as a cone; [P_{min}, P_{max}] is the confidence interval for P at the considered Nex for the binomial distribution, calculated in accordance with [5, p. 42]. It should be taking into account that (N_P+N_R) is not always equal to Nex_k as a discharge can hit both grounded electrodes simultaneously. Influence of the applied DC EF strength (E_0), the level of which is proportional to the corona intensity (see Fig. 3), on the probability of strokes by the high voltage discharges of the grounded electrode with a pointed or rounded tip has been investigated in these experiments.

Table 1

N	Nex	N_P	N_R	P	$\lvert E_0 \rvert$, kV/cm	2R, m	[P_{min}, P_{max}]	Comments
1	34	28	12	2.3	0	0.125	[1.9, 9]	Samples N=1-4 belong to the same statistical population
2	14	13	2	6.5	0.52	0.125	[2.6, 25]	
3	22	19	6	3.2	0.76	0.125	[1.9, 7.1]	
4	22	15	7	2.14	0.95	0.125	[1.5, 3.]	
5	14	4	10	0.4	0	0.045	[0.2, 0.65]	Samples N=5-7 belong to the same statistical population
6	14	5	10	0.5	0.52	0.045	[0.3, 0.7]	
7	22	11	16	0.69	0.76	0.045	[0.48, 0.84]	
8	22	17	9	1.89	0.95	0.045	[1.4,3.2]	Samples N=5-7 and N=8 **do not** belong to the same statistical population

The results of experimental investigations carried out at the following parameters: $|U_{imp}|$=0.86 MV; h=0.93 m; d=1.01; 2R=0.125 m are shown in Table 2. The same notations as in Table 1 were used.

Table 2

N	Nex	N_P	N_R	P	$\lvert E_0 \rvert$, kV/cm	[P_{min}, P_{max}]	Comments
1	45	9	42	0.21	0	[0.12, 0.36]	Samples N=1-3 belong to the same statistical population
2	13	2	12	0.17	0.57	[0.04, 0.38]	
3	24	3	22	0.14	0.76	[0.07, 0.33]	
4	26	9	19	0.47	0.86	[0.33, 0.64]	Samples N=1-3 and N=4 **do not** belong to the same statistical population
5	48	24	41	0.59	0.95	[0.44, 0.7]	Samples N=1-3 and N=5 **do not** belong to the same statistical population Samples N=4 and N=5 belong to the same statistical population

Verification of the hypothesis of the samples belonging to the same general population allows to decide whether the variable factor effects significantly the investigated process (see [5], p. 98). If the samples belong to the same general population, the differences between their relative frequencies are not significant and changing of the variable parameter (E_0) has no significant effect on the probability of the grounded electrode strokes by high voltage discharges. Otherwise, the influence of the E_0 value can not be neglected. Comments to the Tables 1 and 2 indicate when the hypothesis that the samples corresponding to different series of experiments belong to the same statistical population can be accepted, and when it should be rejected.

Comparison of the probabilities (relative frequencies P) of two statistical populations corresponding to the series of experiments N=k (with relative frequency P_k) and N=l (with relative frequency P_l) was performed using z-test (see [5], p. 108):

$$z_{kl} = (P_k - P_l) / \sqrt{\left(\frac{P_k \cdot Nex_k + P_l \cdot Nex_l}{Nex_k + Nex_l} \right) \cdot \left(\frac{Nex_k \cdot (1 - P_k) + Nex_l \cdot (1 - P_l)}{Nex_k \cdot Nex_l} \right)}. \quad (1)$$

The critical value (λ_q), with which z_{kl} value was compared, was assigned with the help of the standard normal distribution as the quantile of the order q=1-α/2 (two-sided test with a significance level α). When α=0.05, the table value gives $\lambda_q \approx 1.96$ (see [5], p. 47). The hypothesis that the samples N=k and N=l belong to the same statistical population was accepted, if the relation $|z_{kl}| < \lambda_q$ was satisfied.

The results shown in Table 1 correspond to the discharges at the voltage pulse front, when the distance between the high voltage and the grounded electrodes is much less than the minimum voltage required for breakdown (d=0.44 m, $|U_{imp}| \approx 0.75$ MV). Voltage measurements were performed using a high-voltage divider; the voltage was fed to an oscilloscope through an optical tract. A measuring spark ball gap with a diameter of spheres equal to 1.5 m was used for calibration of the measuring system. The breakdown 50% voltage was determined by the normalized table [6] for the case of high voltage impulses application to the spark gap from GIN-2.4 when between the balls, separated by 0.351 m distance, breakdown occurred in 50 % of all cases. This voltage level was equal to 862.5 kV. Voltage measurements at high voltage breakdowns in the described system have shown that the breakdowns occurred in the impulse front at the values of the order of $U_{imp} \approx$ -750 kV.

It follows from analysis of the experimental data that if the radius of curvature of one of the grounded electrodes is relatively large (2R=0.125 m), the electrode with a pointed tip is hit mainly regardless the corona presence and level of its intensity in the regimes when discharges occur at the voltage pulse front (see Table 1, experiments N=1-4). Comparison of the relative frequencies (P) of high-voltage discharges strike the pointed electrode with the help of (1) has shown that the samples of experiments N=1-4 belong to the same statistical population (SP), so it is possible to accept the hypothesis that the probabilities of these events are identical, and therefore do not depend on the applied DC EF strength level and corona intensity.

Preferential strokes by high voltage discharges of one of the grounded electrodes with a smaller radius of curvature (2R = 0.045 m) for the discharges at voltage pulse front has been observed (see. Table. 1, experiments N = 5-7). Usage of (1) has shown that samples of the experiments N = 5-7 belong to the same statistical population. However, the situation changes at application of DC EF with greater electrical strength. Thus, when E_{0cr} ~ 0.95 kV/cm authentically significant increase of the number of the pointed electrode strokes by high voltage discharges has been observed (see Table. 1, experiments number N = 8). Thus, there is a certain threshold E_0 value, at which qualitative changes in the processes of formation and propagation of a spark from the grounded to the high voltage electrode take place. It seems that these processes become more intense because of the substantial increase in corona current, and hence the number of avalanches, forming a spark toward the high voltage electrode. For a quantitative description of these processes more research is needed.

The results shown in Table 2 correspond to the high voltage discharges at the tail of the applied voltage, when the distance between the high voltage and grounded electrodes is close to the minimum level required for breakdown at the considered impulses application (d=1.01 m, $|U_{imp}| \leq 1$ MV). Carried voltage measurements at such a case have shown that breakdowns occurred on the impulse tale at the voltage level $U_{imp} \approx$ -863 kV. These experiments were carried for the cases when the radius of curvature of one of the grounded electrodes is relatively large (2R=0.125 m), and this electrode was stricken mainly by high voltage discharges regardless the pre-breakdown corona current level at the tip of the other (pointed) grounded electrode (see Table 2, experiments N=1-5). Comparison of the relative frequencies (P) of high-voltage discharges strike the pointed electrode with the help of (1) has shown that the samples of experiments N=1-3 belong to the same statistical population, so it is possible to accept the hypothesis that the probabilities of all these events are identical, and therefore do not depend on the applied DC EF strength level and therefore on the intensity of corona formation processes. However, authentically significant increase of the number of the pointed electrode strokes by high voltage discharges has been observed at application of $E_0 \geq 0.85$ kV/cm (see Table 2, experiments N = 4, 5). These processes happen at the critical level of E_0 close to the E_{0cr} for the cases of discharges at the impulse voltage front (see Table 1, experiment N=8).

Hence carried physical modeling of high voltage breakdown processes in presence or absence of a corona around the rounded or pointed tips of the grounded electrodes has shown that strength of the applied DC EF does not effect significantly the probability of the grounded electrode hitting by high-voltage discharges, if the applied EF strength levels are below the critical level of the order $E_{0cr} \sim 0.85$ kV/cm. If $E_0 > E_{0cr}$, a significant increase of the probability of strokes of high-voltage discharges of the grounded electrode with a pointed tip, where corona glows most actively, occurs. It is known that at thunderstorm conditions the average strength of the DC EF between thunderclouds and the ground E_{0L} is usually in the range form $E_{0L\min} \approx 0.015$ to $E_{0L\max} \approx 0.05$ kV/cm [2]. Thus, it may be concluded on the basis of the carried investigations that the corona formation processes on the lightning rods can cause significant change in the probability of hitting them by lightning only under certain conditions when increase of the EF strength in the vicinity of their tips reaches a critical level. The maximum EF strength E_{m} on the tips of lightning rods with height h_L increases in comparison with the case of the described experiments with the rods of height h=1.2 m in about h_L/h times [2]. The E_{m} level is proportional to the average applied strength E_0. So the average strength of the DC EF at thunderstorm conditions, at which the corona current growth will be sufficient to increase the probability of hitting of the electrode with a pointed tip, will in h_L/h times less than E_{0cr} and make about $E_{0Lcr} \approx E_{0cr}/(h_L/h)$. So, corona presence can influenced the probability of hitting a lightning rod both at the minimum ($E_{0L\min}$) and at the maximum ($E_{0L\max}$) observed values of E_{0L}, if its height exceeds $h_{L\max} > h \times (E_{0cr}/E_{0L\min}) \approx 70$ m. However, for the upper limit of the E_{0L} range ($E_{0L\max}$) such effects can occur, starting from $h_{L\min} > h \times (E_{0cr}/E_{0L\max}) \approx 20$ m.

Conclusions.

1. Physical modeling of the breakdown processes in long air gaps with the pre-breakdown corona of varying intensity has shown that increase in the number of high voltage strokes to the grounded electrode (in 2.2 – 4.7 times) is observed at a significant amplification of the pre-breakdown corona current intensity (in 1.8 times and more).

2. Extrapolation of the obtained results on the processes taking place in the thunderstorm suggests that the corona discharges will influence the probability of lightning attachment over the range of the electric fields levels between the thundercloud and the earth from 0.015 kV/cm to 0.05 kV/cm for the lightning arrestors of more than 70 m in height.

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УДК 621.316.98

ФІЗИЧНЕ МОДЕЛЮВАННЯ ЕЛЕКТРОФІЗИЧНИХ ПРОЦЕСІВ ПРИ ПРОБОЇ ДОВГИХ ПОВІТРЯНИХ ПРОМІЖКІВ

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Наведено результати фізичного моделювання впливу інтенсивності коронних розрядів на вершинах заземлених об'єктів на ймовірність попадання в них високовольтних розрядів у повітряних проміжках «високовольтний стрижень - стрижень на площині, що заземлена». Досліджувалася система, що складається з вертикального високовольтного негативного стрижневого електрода, що імітує лідерний канал блискавки, і двох заземлених стрижневих електродів, що імітують блискавковідводи: одного зі сферичною і другого із загостреною вершиною. Перед прикладенням високовольтного імпульсу напругою до 1 МВ на високовольтний електрод до електродної системи прикладається постійне електричне поле (ЕП). Експерименти показали, що наявність корони на вершині загостреного електрода достовірно збільшує ймовірність попадання в нього високовольтних розрядів при прикладенні постійного електричного поля, напруженість якого має той самий порядок, що і напруженість імпульсного ЕП. Бібл. 11, рис. 2, табл. 2.

Ключові слова: фізичне моделювання, електрофізичні процеси, ймовірність попадання високовольтного розряду, струм корони, блискавкозахист.

ФИЗИЧЕСКОЕ МОДЕЛИРОВАНИЕ ЭЛЕКТРОФИЗИЧЕСКИХ ПРОЦЕССОВ ПРИ ПРОБОЕ ДЛИННЫХ ВОЗДУШНЫХ ПРОМЕЖУТКОВ

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Приведены результаты физического моделирования влияния интенсивности коронных разрядов на вершинах заземленных объектов на вероятность попадания в них высоковольтных разрядов в воздушных промежутках «высоковольтный стержень – стержень на заземленной плоскости». Исследовалась система, состоящая из вертикального высоковольтного отрицательного стержневого электрода, имитирующего лидерный канал молнии, и двух заземленных стержневых электродов, имитирующих молниеотводы: одного со сферической и второго с заостренной вершиной. Перед приложением высоковольтного импульса напряжением до 1 МВ на высоковольтный электрод к электродной системе прикладывается допробойное постоянное электрическое поле (ЭП). Эксперименты показали, что наличие короны на вершине заостренного электрода достоверно увеличивает вероятность попадания в него высоковольтных разрядов при приложении постоянного электрического поля, напряженность которого имеет тот же порядок, что и напряженность импульсного ЭП.
Библ. 11, рис. 2, табл. 2.

Ключевые слова*:* физическое моделирование, электрофизические процессы, вероятность попадания высоковольтного разряда, ток короны, молниезащита.

Надійшла 08.09.2016
Остаточний варіант 16.12.2016