Journal of Electrostatics 83 (2016) 42–51

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Influence of corona on strike probability of grounded electrodes by high voltage discharges

Marina Rezinkina [a, *], Oleg Rezinkin [b], Franco D'Alessandro [c], Andrii Danyliuk [b], Georgiy Lisachuk [b], Elena Sosina [b], Elena Svetlichnaya [b]

[a] State Institution "Institute of Technical Problems of Magnetism of the National Academy of Sciences of Ukraine", 61106, Kharkiv, Str. Industrialna, 19, Ukraine
[b] National Technical University "Kharkiv Polytechnic Institute", 61102, Kharkiv, Str. Frunze, 21, Ukraine
[c] Lightning Protection International Pty Ltd/PhysElec Solutions Pty Ltd, Hobart, Tasmania, Australia

ARTICLE INFO

Article history:
Received 5 March 2016
Received in revised form
10 July 2016
Accepted 14 July 2016

Keywords:
Corona
High-voltage discharge
Electric field
Strike probability
Physical and mathematical modeling
Lightning attachment

ABSTRACT

This paper presents the results of an investigation into the influence of corona formation processes at the tips of grounded rod electrodes on the probability of those rods being "struck" by high-voltage discharges. Experiments simulating the final stage of the attachment process were carried out with a composite voltage comprising a simultaneously applied impulse and DC potential of different levels to grounded rod electrodes simulating lightning rods, featuring either a spherical or pointed (conical) tip. The experiments show that corona does not influence the probability of the electrode being struck until a critical electric field (EF) strength is reached.

1. Introduction

The question whether corona formation around the tips of grounded rod electrodes influences the probability of rods struck by natural lightning or a simulated discharge utilizing high-voltages has attracted much attention in the literature, e.g., see Refs. [1–3]. However, experimental data regarding the nature of this influence is often contradictory [1]. For example, studies conducted in a laboratory often show no significant correlation between the shape of the rod conductor tip (pointed or rounded) and probability of it being struck by high voltage discharges, but field tests under natural lightning conditions atop a mountain have shown that lightning strikes only lightning rods with "blunt" tips [2]. Bazelyan and Raizer [3] have carried out many numerical calculations that show that corona development on electrode tips hinders the formation of upward leaders and their propagation towards a downward lightning leader.

D'Alessandro and Berger [4] presented experimental studies of the dependence of corona current magnitude on EF strength and the shape of the tip of grounded rod electrodes simulating lightning rods. However, the influence of the amount of corona around grounded electrodes on the strike probability of high-voltage sparks was not investigated.

Physical modeling may be used to assess whether pre-breakdown corona around the grounded electrode tip and the magnitude of its current has an influence on the probability of the attachment of high-voltage discharges to the electrode. Such simulations involve a comparison of the number of strokes from a high-voltage rod electrode to grounded rod electrodes with different tips, keeping the distance constant. The high-voltage rod electrode is used to simulate the lightning downward leader channel. The magnitude of corona current may be varied by changing the magnitude of the applied DC EF as well as the radius of curvature of the grounded electrode tips. The results obtained can be interpreted with the help of mathematical modeling of the EF distributions in the considered systems.

In carrying out such simulations, it should be taken into account that the majority of cloud-to-ground lightning discharges have a negative polarity [3]. The average EF intensity required for

* Corresponding author.
E-mail address: Rezinkina@nas.gov.ua (M. Rezinkina).

http://dx.doi.org/10.1016/j.elstat.2016.07.005
0304-3886/

development of positive polarity leader channels ($E_+ \approx 5 \times 10^5$ V/m) is about half the intensity necessary for the development of negative polarity leader channels ($E_- \approx 10^6$ V/m) [3].

Discrepancies in published literature exist with regard to the results of strike probability tests in a laboratory using high-voltage discharges and grounded electrodes with sharp or rounded tips. Often, these discrepancies are due to different experimental conditions. As shown in Ref. [1], the results of indoor experiments for determination of the number of breakdowns in an inverted rod-plane system with grounded rods of height $h = 2.5$ m using pointed and rounded tips differ from similar tests carried out outdoors. In the first case (indoor tests), when the distance between the tips of the grounded rods and the high voltage (HV) plane was 5 m, a greater number of high-voltage discharges occurred at the rod with a pointed tip. In the second case (outdoor tests), with a rod height of 5 m and plane height of 10 m, the number of high-voltage discharges to each rod was approximately equal. The authors explain the advantage of the sharp rod over the blunt one in the first set of experiments by the influence of early corona from the sharp rod, where the corona space charge decreases the electric field near the adjacent rod. However, the same processes occur in the second set of the experiments without such an effect. This difference may be due to the larger horizontal distance between the grounded rods in the outdoor tests than the indoor tests (6 m and 3 m respectively), i.e., less influence of the corona space charge from the pointed rod on the EF near the adjacent rounded rod. Such differences may also be caused by the longer upward leader breakdown distance and greater tortuosity in the outdoor tests and therefore less relative influence of the earlier start of corona from the pointed rod.

Both of the aforementioned experiments utilized an inverted rod-plane gap arrangement, which essentially constitutes a study of corona discharge and upward leaders. A “descending lightning leader channel” creates different EF and space charge distributions and, therefore, different characteristics of spark development. Such an arrangement, of relevance to the present paper, will be henceforth referred to as a “rod-rod” configuration.

In Ref. [1], the results of outdoor experiments with a rod-rod configuration were also presented. In this case, the air gap, d, was 26 m. An outcome of the experiment was an approximately equal number of strikes by high-voltage discharges to both electrodes. In this experiment, $d \gg h$ and the length of a streamer zone (d_{str}, in which development of sparks from the high-voltage electrode occurs). Under such conditions, the random process by which the high-voltage discharge “selects” a strike point is superimposed on an additional random process, namely that of the tortuous path of the high-voltage sparks approaching the ground. Moreover, 35% of the strikes terminated on the ground in this case. Because of such excess of d over h and d_{str}, increase of the EF stress in the vicinity of the grounded rods tips, as well as appearance of a corona on them can influence the orientation of the descending high-voltage sparks only in the final stage of progress towards the ground. Such an orientation begins at a random point over the ground and at a random distance between the descending leader channel tip and the grounded rods tips.

To eliminate the effect of the aforementioned additional random process, shorter discharge gaps d comparable with d_{str} length may be chosen. Thus, under conditions of indoor experiments, the application of a negative polarity impulses with amplitudes up to 1 MV to the suspended high voltage electrode will result in a maximum streamer zone length not exceeding 1 m.

It is known that the breakdown character depends on whether upward sparks to a high voltage electrode from the grounded rod electrodes will or will not develop. To simulate the processes in the first case (*with* upward spark development), it is possible to use a system in which $d \sim d_{strm}/2$ to provide reliable conditions of upward spark propagation from the grounded rods, if the conditions of such spark appearance are fulfilled. To simulate the processes in the second case (*without* upward spark development), a system with $d \sim d_{strm}$ may be used. In the first case, breakdown of the air gap will most probably occur at the front of the applied high voltage impulse. In the second case, breakdown will most probably occur on the tail of the applied high voltage impulse. Experiments with such small air gap have some disadvantages if compared with real lightning spark lengths, but they isolate the problem to a question of whether corona around the tips of grounded electrodes has any influence on the strike probability of a high voltage discharge.

A full-scale physical simulation of the lightning attachment process is not possible. Although the process of lightning leader orientation does not comply with the laws of similarity, laboratory experiments do permit a better understanding of the mechanisms of long spark orientation [3].

2. Analysis of laboratory tests

2.1. Corona formation processes as function of electrode tip shape

Modeling of processes of high-voltage discharge attachment to grounded rod electrodes simulating lightning rods was carried out with the following setup. A high voltage impulse Marx generator (HVIMG) with 12 stages, having a discharge capacity $C_{sh} = 7.1$ nF and stored energy up to $W_{\max} = 3.6$ kJ, was used as the source of impulse voltages of negative polarity. A standard lightning impulse waveshape was used, namely 1.2/50 μs An electrical schematic of the high-voltage setup along with photographs of the actual arrangement are shown in Fig. 1. The maximum negative impulse voltage, U_{imp}, of 862.5 kV was chosen in order to provide breakdown of the electrode air gaps up to 1 m.

A negative DC voltage U_{con} was applied from the output of the high voltage source 4 via resistor $R2$ to the conductive plane 6 with dimensions 3 × 3 m (see Fig. 1), commencing about 3 min before the application of the impulse voltage. So, a “composite voltage” consisting of impulse and DC voltages was used for the tests. The U_{con} values ranged from 120 kV to 200 kV. The minimum level of U_{con} was chosen to provide pre-breakdown electric stress sufficient for corona appearance on the electrode with a conical tip, but not on the electrode with a spherical tip. U_{con} levels were increased further (up to 200 kV) until some changes in the probabilities of high voltage discharge strikes were observed. In order to avoid corona discharges from the corners, edges and fasteners of plane 6, foil screen was used to round off these features to radii of curvature of more than 100 mm. Plane 6 was suspended at a height of $D = 2.1$ m above the ground plane 5 (Fig. 1). The DC electric field generated between planes 5 and 6 at the application of U_{con} simulates conditions of pre-stroke thunderstorm in which the ambient EF may cause corona on the tips of grounded electrodes. The magnitude of the DC electric field is given by $E_0 \approx U_{con}/D$, provided there are no “fringing effects” at the edges of plane 6. At a sufficient level of E_0, pre-breakdown corona discharges occur at the tips of the grounded rod electrodes. The intensity of pre-breakdown corona discharges may be assessed by measuring the average corona current (I_{cor}) before the application of the impulse voltage.

The measured corona current is comprised of two components. One component is the diffuse form of gas discharge (often called “glow corona”) and the other component appears as incomplete plasma channels (often referred to as “streamer corona”) in the air gap between the high-voltage plane electrode (6, Fig. 1*b*) and the grounded electrodes with different tip geometries (7, Fig. 1*b*). The amplitude of the current impulses of streamer corona is far greater than the average current of the diffuse corona, but the duration of