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A fractal model of discharge interception probability of a vertical grounded rod in the presence of a neighboring object

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ABSTRACT

An experimental investigation on the lightning discharge interception probability of a vertical grounded rod when inserted in a rod-plane gap, as affected by the presence of a neighboring grounded object (rod) is presented. The height of the two grounded rods (simulating a protective and a protected object against lightning) and their separation distance and placement with respect to the energized rod were considered as influencing parameters on breakdown voltage and time, thus also on the discharge interception probability, under negative lightning impulse voltages. The discharge interception probability of the vertical grounded rod is strongly affected by the height and position of the neighboring rod; it significantly reduces when the separation distance between rods decreases, especially as the height of the rods increases. In the presence of the neighboring rod breakdown to the vertical rod occurs sooner at higher instantaneous voltages. A fractal model describing the lightning interception probability in the evaluated electrode arrangement is developed; the electrical discharges, emanating from both energized and grounded electrodes, evolve randomly in the space where the electric field is most intense. By considering also the voltage drop along the discharge path at each evolution step a satisfactory agreement between simulation and experimental results has been achieved.

1. Introduction

Lightning is a natural phenomenon that very briefly comprises an ionized conducting path extending over several kilometers. The potential difference between the ground and the space charge of thunderstorm cloud rises to many hundred million volts and the lightning stroke current varies from thousands to hundreds of thousands amperes [1–6] making inevitable the recourse to adequate protection. Lightning protection by means of simple vertical rod conductors has been known since 1752, after the first concepts of Benjamin Franklin and the first experimental evidences brought by French scientists [7]. Up to now, the physical behavior of a rod experiencing thunderstorm conditions is not fully understood. In particular, the performance of lightning protection systems utilizing Franklin rods is most commonly assessed according to the Electrogeometrical model [8–10], which is often not confirmed in actual conditions. In fact, this model presents many imperfections such as the fact that it does not take into account proximity effects.

In recent years, significant effort has been made to better understand the complex phenomenon of electrical discharge. Valuable information has been gained by introducing a Fractal approach to study the dynamics of electrical discharges [11–21].

Niemeyer et al. [15] have applied the fractal concept to dielectric breakdown; they introduced a stochastic model (NPW) to simulate the growth of a fractal structure which resembles a Lichtenberg figure. They determined the Haussdorff dimension and other fractal properties of the structure and showed that there are close relations to other fractal structures.

Further development of the NPW model was realized by Femia, Niemeyer, and Tucci [16], who made rigorous the studies previously conducted. They noted that the general topological characteristics of electrical discharges branches have been shown a fractal quality and that computer models can be developed replicating the general aspects of the discharges. Petrov and Petrova [17], pulled together many of the most advantageous aspects of the previous studies. In their paper, they studied intra-cloud lightning, that is, lightning discharges which travel between clouds rather than between a cloud and the ground. Then, in 1994, they published their second work [18]. In this paper they took the same methodology they developed in their previous paper but focus more directly on lightning strikes to earth, in particular to structures, either with or without modeled lightning rods nearby. They discussed the effectiveness of the lightning rods protecting the structures based on their results. In 1998, Petrova [19] presented a paper at the

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International Conference on Lightning Protection, including various cases similar to the 1994 study and discussing the protective zone afforded by lightning conductors. In the same period, V. A. Rakov and M. A. Uman [20] made a review of the lightning return stroke models. In most of models, the return stroke channel is assumed to be straight. However, the lightning channel is very irregular. In fact, it is oblique, tortuous and branching. Considering all these properties, they concluded that the characteristic of fractal can be used to model lightning. In 2003, Petrov et al. [21] extended their earlier work to more elaborate grounded structures in combination with more elaborated series of lightning rods.

This paper presents an experimental investigation on the lightning discharge interception probability of a vertical grounded rod when inserted in a rod-plane gap, as affected by the presence of a neighboring grounded object (rod). The height of the two grounded rods and their separation distance and placement with respect to the energized rod were considered as influencing parameters on breakdown voltage and time, thus also on the discharge interception probability. Based on the stochastic model of discharge growth proposed by Niemeyer et al. [15], a fractal model describing the lightning interception probability in the evaluated electrode arrangement has been developed; the electrical discharges, emanating from both energized and grounded electrodes, evolve randomly in the space where the field is most intense. By considering also the voltage drop along the discharge path at each evolution step a satisfactory agreement between simulation and experimental results has been achieved. It must be noted that this study does not aim to simulate the entire lightning flash phenomenon; it focuses on the final jump phase, where lightning interception by a grounded object may occur or not.

2. Experimental setup

In accordance with previous laboratory experiments on lightning discharge interception probability [22], in the present investigation, a four electrode configuration, comprising of an earthed plane and three cylindrical rods 1.2 cm in diameter with hemispherical tip, has been used (Fig. 1). The energized rod was hanging over the floor of the laboratory (earthed plane) at 77 cm above it and the grounded rods were placed at several separation distances from the energized rod (Fig. 1). The two grounded rods, neighboring object “hr” and protective “hp”, were inserted in the rod-plane gap at several lateral distances “Xr “and “Xp”, respectively, from its vertical axis (Fig. 1). The height and position of the grounded rods were varied to investigate the discharge interception probability of the grounded rods. The gap was stressed by standard lightning impulse voltages (1.2/50 μs) of negative polarity, produced by a ten-stage Marx generator 1 MV/7 kJ. The capacitor divider of the Marx generator and a 600 MHz bandwidth digital oscilloscope enable the monitoring of the voltage stressing the gap.

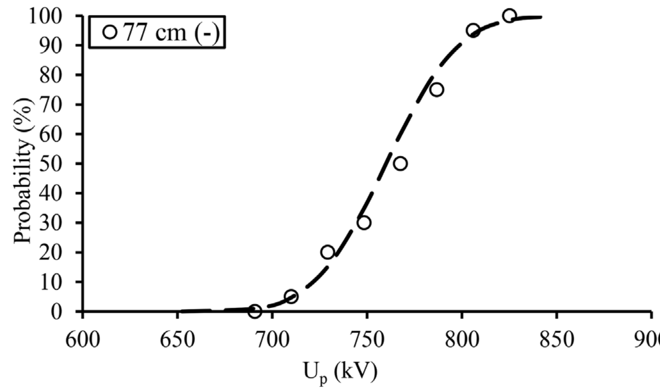

Fig. 2. Breakdown probability distribution; 77 cm rod-plane gap under negative standard lightning impulse voltage; fitting curve according to Normal distribution.

2.1. Breakdown probability distribution of the pure rod-plane gap

Class 1: Multiple-level tests according to the relevant IEC Standard [23] were conducted to determine the breakdown probability distribution of the pure rod-plane gap; at voltage levels gradually increasing in amplitude, 20 impulse voltage shots were applied at time interval of 1 min. The so obtained breakdown probability distribution is shown in Fig. 2, where it is obvious that it can be satisfactorily approximated by the Normal distribution. Thus, the breakdown voltage of 840 kV corresponding to 97.5% breakdown probability was easily obtained; thereafter this voltage was used to investigate the lightning discharge interception probability of the grounded rods (Fig. 1).

2.2. Measurement procedures

When a grounded rod is inserted in the rod-plane gap, at applied voltages always causing breakdown the discharge terminates either to the plane or to the grounded rod or rarely to both grounded electrodes

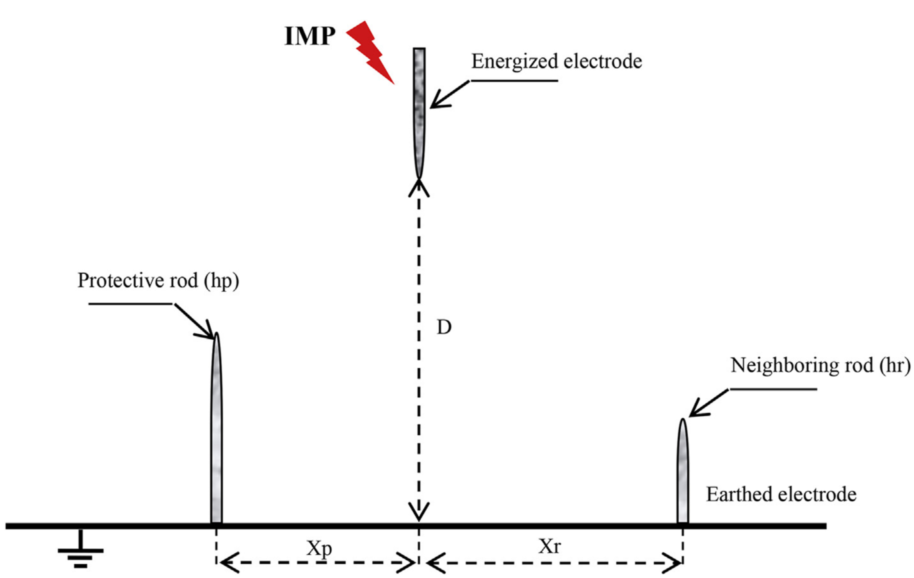

Fig. 1. Schematic diagram of the electrode configuration; D: Striking distance to ground.