Journal of Electrostatics 76 (2015) 208–215

Contents lists available at ScienceDirect

Journal of Electrostatics

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

Leader channel models for long air positive electrical discharges

Oscar Diaz [a,*], Liliana Arevalo [b], Vernon Cooray [a]

[a] Lightning Research Group, Division of Electricity, Ångström Laboratory, Uppsala University, Box 534, SE-75121 Uppsala, Sweden
[b] ABB Power Systems HVDC, SE-77180 Ludvika, Sweden

A R T I C L E I N F O

Article history:
Received 25 March 2014
Received in revised form
26 May 2015
Accepted 26 May 2015
Available online 12 June 2015

Keywords:
Leader channel model
Long air gap discharge
Switching impulses

A B S T R A C T

The models proposed for the positive long air gap electrical discharge can be considered to be either engineering or physical in their approach. In this work, we make a general review of the available models and use two of them for a comparison with experimental data. Common underlying assumptions were found in most of the models analyzed. The comparison with the experimental data revealed that the results obtained from the models were a good representation of the physical situation when the leader potential distribution and the leader-corona region evolution were described with certain physical assumptions.

1. Introduction

Electrical discharges produced in a long air gap in a laboratory have been the object of extensive study in the high voltage engineering field, mainly in relation to high voltage insulation design, and in the study of lightning modeling and protection. Important contributions have been made during the last few decades, both experimentally [1,2,7] and theoretically [3–6,8–15]. Given the importance of a good estimation of the 50% breakdown voltage parameter for different electrode configurations, several tasks have been performed to test this insulation engineering parameter and important guidelines were developed to improve design procedures and recommendations.

Among the experimental investigations, the work by 'Les Renardières' group during the 70's and 80's stands out, because their results have been used by several authors over a substantial period of time ever since [5,6,8,11–15]. For the case of the basic electrode configuration of rod-to-plane, records of the voltage, current, electric field, and optical radiation were reported. Some of the main conclusions obtained from these studies were the physical processes involved in positive discharge propagation, among other things, that the leader channel propagates along the air gap thanks to the leader-corona region (LCR) in front of the leader tip, where the latter might extend several meters further along the leader channel.

From these experiments, models of the long laboratory air gap discharge have been proposed. One important element common to these models is the way the leader channel is represented. Depending on the level of detail used, and the simplifications and assumptions, the leader channel models can be either of engineering or physical type. The engineering models incorporate existing knowledge of the general physical discharge characteristics required to predict the 50% breakdown voltage and its statistical variation [22]. For the case of the physical models, the conservation of mass, momentum and energy, continuity of charged, neutral and excited species available during the discharge development underpin the calculations coupled with basic electromagnetism. Additional information like the number and type of chemical reactions between different species, the temperature, channel radius, potential distribution, LCR limit and leader tip location in time and space, might be obtained as well. A detailed analysis of the other processes involved in the complete long air gap electrical discharge like the streamer inception (first corona), the streamer to leader transition (second corona), and LCR representation are beyond the scope of this work. A detailed analysis of these elements can be found in the literature [3,9,22].

In most of the articles on the theoretical modeling of long air gap electrical discharges, a specific way of considering the leader channel is assumed, depending upon each author's particular knowledge or research interests, without having to think through the different possibilities available to represent the leader. In the present work, we considered different engineering and physical leader models, looking at the basic concepts and the assumptions made. From the models examined, two were selected to perform a

* Corresponding author.
E-mail address: oscar.diaz@angstrom.uu.se (O. Diaz).

http://dx.doi.org/10.1016/j.elstat.2015.05.026

more detailed study, including one of each type. They were compared with experimental data by performing a numerical simulation of the discharge process, looking at the potential evolution along the leader channel and the spatial location of the leader tip and LCR region.

In Section 2, a general description of the positive discharge in a long laboratory air gap is given, mentioning its main characteristics. In Section 3, a summary of the engineering and physical leader channel models is presented and their main assumptions and a general description are depicted. In Section 4 a comparison is made between the models presented, based on the experimental results.

2. Long gap laboratory positive discharge generalities

The rod-to-plane configuration has been broadly tested for switching voltage impulses in long air gap laboratory discharge. Schematic descriptions of the elements that compose a full discharge are presented in Fig. 1.

The positive discharge process is initiated with the corona inception at time t_1. Once a threshold critical gradient is reached in the vicinity of the electrode surface, some branched streamers initiate from a common point. At t_2 the leader inception takes place after those first streamers have produced the sufficient charge to initiate the leader channel (a slightly luminous path) at the place the streamers originated from. At the tip of this newly created leader channel, the LCR sustains the discharge advance by feeding charge to the channel; which will eventually thermalize a section of the channel increasing its electrical conductivity. This whole effect causes the leader to propagate towards ground along the gap provided that the LCR has an average potential gradient high enough to maintain the ionization processes, usually between 400 and 500 kV/m for atmospheric air. In continuous propagation, the leader tip moves at an almost constant velocity between 1 and 2 cm/μs, with a current value close to 1 A and an average internal electric field of 100 kV/m. The final jump condition will happen once the LCR reaches the grounded plane at time t_3 [3,9].

Different elements of the previously described process, like the streamer inception, the leader inception and the LCR characteristics have been studied by different authors. The concept of a streamer inception level based on surpassing a minimum amount of ionic charge at the streamer discharge head is used by most of them [3–6,8,9,11–15,22].

For the leader inception, a variety of approaches have been proposed, considering: how the leader channel stem emerges by reaching a certain charge threshold [3–6,19], how the densities of particles and chemical reactions along the LCR change [20,21], and how the energy available in the LCR needs to be high enough to cause thermalization of a new segment of the leader channel [22], among others. A simple way of describing this process was proposed by Aleksandrov [19] where the electrons created at the LCR drift towards the anode, loosing their energy by collisions with gas molecules, heating up the gas. As a consequence, the common point, i.e., the place where these streamers meet, will develop a high conductivity, helping the creation of a defined conducting channel.

The LCR, as the leader channel electric charge provider, has been modeled by considering different possible geometries: segments [5,6], cones [11,12], and enclosed surfaces defined by an electric field boundary [14,15]. The conventional way to define this enclosed region is to assume a minimum for the average potential gradient over the whole region.

Once the leader channel and the LCR continuously propagate along the gap and the latter reaches the grounded plane, the final jump condition has been attained. This condition has been considered by most of the authors since it is unlikely that the discharge does not reach the arc state once the LCR connects the leader tip to the grounded plane.

3. Leader channel models

Detailed information on some important engineering leader channel models can be found in the literature [18,22,24–26]. From this body of research, a brief description of the models proposed by Jones [22], Lemke [24], Hutzler [25], Bazelyan [26] is included in the present work. In addition, the Rizk model [16,17] has been presented in greater detail since it is used for comparison in § 4. Referring to the physical models, those from Waters [2,22,23] and Gallimberti [2,3] were analyzed, being more detailed the presentation of the latter since the discretization of this model done by Lalande [5,6] was used for comparison in § 4. Common elements and assumptions were found while analyzing the afore-mentioned models. The assumption of a constant potential gradient required to sustain the streamer discharge E_{SC} in the LCR is made in both the engineering and the physical models, such as those of Jones, Hutzler, Bazelyan, Waters, Gallimberti/Lalande. At the same time, the constant charge per unit channel length q_L is assumed by Hutzler, Waters and Gallimberti/Lalande.

3.1. Engineering leader channel models

3.1.1. Jones model [22]

This model attempts to explain the U-shape dependence of the breakdown voltage on the time-to-crest. The model indicates that,

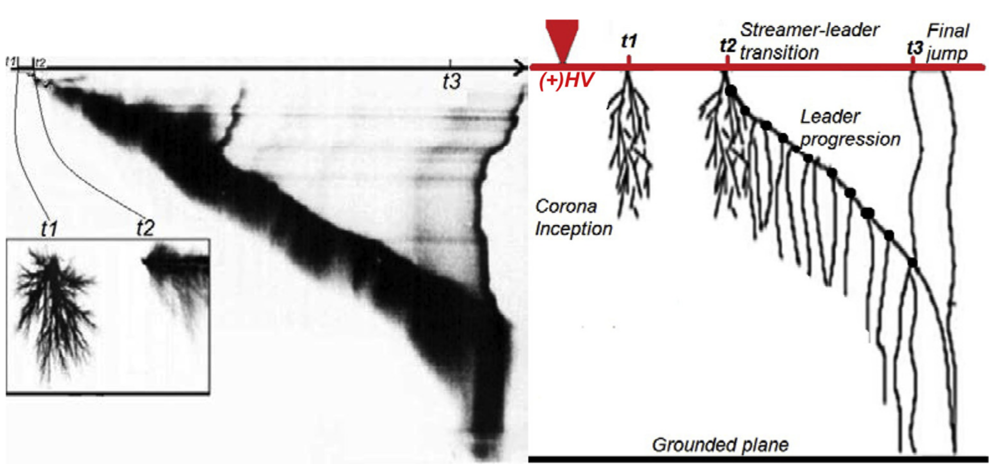

Fig. 1. Streak photograph and schematic representation of the positive long gap laboratory discharge (adapted from Ref. [5]).