Numerical simulation of long laboratory sparks generated by positive switching impulses

Liliana Arevalo a,*, Vernon Cooraya a, Raul Montano b

a Division for Electricity and Lightning Research, Ångstro¨m Laboratory, Department of Engineering Sciences, Lagerhyddsvagen 1, Box 534, SE-751 21, Uppsala University, Sweden
b High Voltage Valley, Ludvika, Sweden

ARTICLE INFO

Article history:
Received 15 September 2008
Received in revised form 19 November 2008
Accepted 31 December 2008
Available online 7 February 2009

Keywords:
Discharge
Leader
Modeling
Switching

ABSTRACT

A numerical methodology using two different leader channel criteria has been implemented. The methodology is based on Bondiou and Gallimberti’s proposition [A. Bondiou, I. Gallimberti, Theoretical modelling of the development of the positive spark in long spark, J. Phys. D: Appl. Phys. 27 (1994) 1252–1266]. The leader channel criteria used are Rizk engineering criterion [Rizk, A model for switching impulse leader inception and breakdown of long air gaps, IEEE Trans. Power Deliv., 4(1) (1989)] and Local thermodynamic – L.T.E. – physical concept [I. Gallimberti, The mechanism of the long spark formation, Colloque C7, Phys. (supplement au nro 7, Tome 40) (July 1979) C7–193]. The methodology was tested in three different cases; a deterministic case, a statistical variation and a typical constant level test. Deterministic calculation considered corona inception using stabilization corona electric field criterion of Gallimberti [I. Gallimberti, The mechanism of the long spark formation, Colloque C7, Phys. (supplement au nro 7, Tome 40) (July 1979) C7–193] and the leader moving as segments. The statistical simulation has two different statistical delays, one at inception and the other due to the tortuous characteristics of the leader channel. The constant level test consists of 200 positive switching impulses with the same characteristics such as maximum applied voltage, time to crest and time to fall. Time to breakdown and breakdown voltage were found based on the results obtained from the constant level test characteristics. All the numerical results presented are based on experimental conditions reported in [Les Renardie`res Group, Research on long gap discharges at Les Renardieres, Electra N 35 (1973)] from the world class research group namely Les Renardieres Group.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Long gap discharges under positive switching impulses have been studied experimentally by different authors [4,5]. Based on these results different engineering and physical models have been proposed. Engineering models are based on empirical formulations as the critical radius concept of Carrara and Thione [6], Leader inception voltage of Rizk [2] and the Leader intensification criterion of Petrov and Waters [7] and others. Those empirical models have given a practical solution for electrical design but cannot account relevant factors associated with the physics of the discharge.

Meanwhile, physical models are dedicated deeply in physics and particles behavior. Gallimberti’s model [1] introduced the physic of the particles and Goelian and Lalande simplified model [8] recalculates the background potential for each leader segment. The limitations of these models are that they required very good computational resources, resulting in lengthy methodologies and long time consuming simulations.

2. Methodology

The proposed methodology consisted on a hybrid method between the physical model of Bondiou and Gallimberti [1] and the implementation of two different models for the leader channel as the engineering approximation of Rizk [2] and the physical model of Gallimberti’s [3]. The calculation was divided in two parts, the evaluation of the corona inception and the leader development.

In general the calculation started when the corona stabilization criterion proposed by Gallimberti [3] was fulfilled. A double exponential source [10] was applied to the high voltage electrode and the corona criterion was evaluated [1]. If corona zone criterion was not fulfilled the double exponential source continue increasing its voltage magnitude. When the criterion was fulfilled, a streamer
corona started from the high voltage electrode and a new stage started called “unstable leader”.

To decide if there is or not “stable leader inception”, the electric potential distribution in time and the charge in the channel were evaluated. The leader phenomenon was divided in two stages: (1) increment of voltage source over the potential profile and (2) the effect of the leader advance over the potential distribution. The electric potential distribution profile for the next time step was a linear combination of the potential drop due to the corona zone, the voltage drop due to the advance of the leader and the potential distribution of the double exponential source. Comparing the potential characteristics for two continuous times it is possible to evaluate the charge on the leader channel and if there is or not stable leader inception. A detailed description of the methodology developed by Arevalo et al. was presented on [9].

Two different statistical delays were applied to the deterministic method, i.e., the inception of the corona and the tortuous of the leader channel. The former is associated with the necessary condition of the presence of a primary electron capable to produce inception. In order to take into account the time delay associated with the channel tortuosity a normal distribution based on experimental results was used to describe the deviation of the discharge angle [10]. The flow chart of Fig. 1 represents the basic characteristics of the numerical method.

To introduce a more physical approach to the voltage drop on the leader channel, Gallimberti’s concept of “local thermodynamic equilibrium” [3] was used. The leader was decomposed in elementary segments with length \( dl \), temperature \( T \), pressure \( P \) and molecular density \( n \) that is uniform along the channel. Therefore, the potential drop \( \Delta U \) in the segment \( i \) will be: \( \Delta U_i = E_l \cdot dl \) where \( dl \) is the length of the segment \( i \) and \( E_l \) is the potential gradient of the segment of length \( l \).

Gallimberti’s model gives the evolution of the internal electric field \( E_l \) in function of the injected current supposing that leader channel conductivity is essentially controlled by electronic collisions between neutral molecules and accelerated electrons on the electric field \( E_l \). This hypothesis is justified because the temperature of the leader channel never will be higher than 5000 K. It supposes that all the injected current \( I_i \) is used to dilate the leader and the expansion is made a constant mass. The formulation describing this hypothesis results in the following set of equations:

\[
\frac{\pi \cdot a_{i}^{2} \cdot n_{0i} \cdot dl_i}{\gamma - 1} = \pi \cdot a_{i}^{2} \cdot n_{i} \cdot dl_i
\]

(1)

\[
\gamma \cdot P_0 \cdot \frac{d}{dt} (\pi \cdot a_i^{2}) = E_l \cdot I_i
\]

(2)

where \( a_i \) is the radius of leader segment in a determined time instance, \( n_i \) is the neutral molecules density in a determined time instance; \( P_0 \) and \( n_0i \) initial conditions for the leader formation. \( P_0 \) as atmospheric pressure, \( \gamma \) ratio between specific heat at pressure and volume constant, \( d(\pi a_i^{2}) \) variation of the section of the leader, \( E_l \cdot I_i \) injected power into the channel during a time step \( dt \).

Based on equation (2) it is possible to calculate the channel section for a next time step in function of the time instance \( t \) and the internal electric field and the charge \( I_i \cdot dt \)

\[
\pi \cdot a^2 \cdot (t + dt) = \pi \cdot a^2 (t) + \gamma \cdot \frac{1}{\gamma \cdot P_0} E_l \cdot I_i \cdot dt
\]

(3)

As the mass is constant from the molecules density can be written as:

\[
n(t + dt) = n(t) \frac{\pi \cdot a^{2} (t)}{\pi \cdot a^{2} (t + dt)}
\]

(4)

and using the hypothesis that \( E_l/n \) is constant; the internal electric field in time will be equal to:

![Fig. 1. Flow chart corona inception and leader propagation. Methodology proposed for the calculation of corona inception (left) and leader propagation (right). The calculations included time delays related to the leader inception and random angle deviation of the leader channel.](image-url)