Electric Power Systems Research 139 (2016) 32–36

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Parameter variation in leader channel models used in long air gap discharge simulation

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ARTICLE INFO

Article history:
Available online 6 January 2016

Keywords:
High voltage techniques
Long gap laboratory air gaps
Leader channel model
Leader-corona region

ABSTRACT

Theoretical models have been developed to predict the 50% breakdown voltage of long air gaps arrangements, based on the physics of the discharge. These models are capable of estimating electric fields, leader and streamer region propagation, among others. An important parameter within this calculation is the leader model and its electric potential distribution along the discharge channel. In the present work, we compared engineering and physical leader models against experimental data recorded for a rod-to-plane electrode arrangement tested with switching-like voltage impulses. The analysis showed that the leader channel evolution depends strongly on the potential gradient assumed to sustain streamers.

1. Introduction

The modeling of the electrical discharge occurring in long laboratory air gaps has been of great interest of scientists and engineers working in the high voltage equipment design [1–8]. Important contributions have been done during the last decades, both experimental [1,2] and theoretical [3–7]. The theoretical understanding of the discharge phenomena is closely related with experimentation, since physical models depart from observation of measurable physical variables. 'Les Renardières' research group [1,2] presents an experimental work where electric field, potential, current and radiation for different electrode arrangements are measured. The physical processes involved in the positive discharge are analyzed, like the leader propagation along the air gap due to the leader-corona region (LCR) in front of the leader tip. Their results have been used by other authors working with electrical discharges modeling [5–13].

The leader channel models can be either engineering or physical. The engineering leader models aim to predict the 50% breakdown voltage and its statistical variation [16,17]. For the physical leader models, a better description of the phenomena involved is obtained by solving equations of the conservation of mass, momentum and energy, continuity of charged, neutral and excited species coupled with basic electromagnetics. In most of the scientific work related to theoretical modeling of long air gap electrical discharges, there has been little study on comparing different leader models and their influence on the whole discharge model output.

In the present work we analyzed two leader models comparing them against experimental data. Based on the methodology presented in [5–7], a set of numerical simulations were set to compare the output of each model while their input parameters were modified. A more detailed study on leader channel models can be found in a different publication [19]. The detailed analysis of the remaining processes involved in the full long laboratory air gap discharge, like the streamer inception, the streamer to leader transition, and LCR representation were out of the scope of this work. A detailed explanation of these discharge model stages can be found elsewhere [3,7,16].

2. Long gap laboratory positive discharges

2.1. Generalities

The streamer inception (also known as first corona inception) marks the initiation of the positive discharge event. Once a threshold critical gradient is surpassed at the vicinity of the high voltage electrode surface, branched streamers are created at common point near the rod tip. After these streamers have produced a certain amount of electrical charge required to thermalize the first section of the leader channel, the leader inception (also known as streamer to leader transition) takes place. At the tip of the newly created leader channel, the LCR sustains the discharge advance by further supplying electric charge, continuously thermalizing new sections of the leader channel. This causes the leader to propagate

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http://dx.doi.org/10.1016/j.epsr.2015.11.033

further along the gap if it has an average potential gradient high enough to sustain ionization processes in the LCR, ca. 450 kV/m for atmospheric air. In continuous propagation at laboratory gaps, the leader tip moves at an almost constant velocity and current, mainly dependent on the background electric field rate of change in time [21]. The final jump condition is achieved when the LCR reaches the grounded plane [3,7]. When the discharge achieves this final stage, the connection of the leader channel with the grounded plane happens and the complete breakdown is almost inevitable.

2.2. *Leader channel models*

The selected models, one engineering and one physical, have been used in works related to electrical discharges in air in long gaps and lightning attachment [5,6,11,15]. They have been implemented in routines where the estimation of the potential distribution along the leader is required within a given methodology to predict lightning attachment to grounded structures [5,11] or to estimate breakdown voltages of specific electrode arrangements [6,15].

2.3. *Engineering model of Rizk [14,15]*

This model is based on an electrostatic representation of the LCR and the leader channel itself, including also concepts from Jones [17] and Hutzler [18]. Our main interest on this model was the potential distribution along the leader channel for a rod-to-plane electrode arrangement, mainly function of the channel length l_Z (1):

$$\Delta U_l = l_z \cdot E_\infty + x_0 \cdot E_\infty \cdot \ln\left[\frac{E_i}{E_\infty} - \frac{E_i - E_\infty}{E_\infty} e^{-l_Z/x_0}\right] \qquad (1)$$

where E_i and E_∞ are the initial and ultimate values of the leader gradient. x_0 is a space constant estimated by $x_0 = v_L \cdot \theta$, being v_L the leader propagation average speed and θ is a time constant with value $\theta = 50\ \mu s$.

2.4. *Physical model of Lalande [5,6]*

The original model from the Gallimberti [2,3] is a simplified non-local thermal equilibrium model for a weak shock that considers the channel as a homogeneous cylinder surrounded by a dense shell. Over its cross section the pressure, temperature and particle density are constant. Lalande [5,6] discretizes the equation describing the leader radius evolution, in a way that the leader is now composed of discretized segments; and within each segment its the radius and internal electric field change every time step (2):

$$a_j^2 = a_{j0}^2 + \frac{(\gamma - 1) \cdot E_j \cdot \Delta Q_{SC}}{\gamma \cdot \pi \cdot p} \qquad (2)$$

where a_j and a_{j0} are the present and previous leader segment radius, E_j is the internal electric field of the leader segment, q_L is the lineal charge per unit length along the leader channel (assumed constant), Δx_L is the leader segment length, γ is the constant ratio between specific heats ($\gamma = c_p/c_v$), and p is the constant pressure inside the leader channel. Based in a constant particle number, i.e. $N_j\ \pi a_j{}^2 = N_{j0}\ \pi a_{j0}{}^2$ (where N_j is the particle density of the j-segment), the reduced electric field is constant at each segment for any given time. The evolution of the leader segment internal electric field can be estimated as:

$$E_{Lj} = \frac{E_{Lj0}}{N_{j0}} N_j \qquad (3)$$

where the subindex '$j0$' in the electric field (E_{j0}) and particle density (N_{j0}) indicate the variable previous value in the j-segment. By knowing the evolution of the internal electric field, it is possible to estimate the leader tip potential (U_{Ltip}):

$$U_{\mathrm{Ltip}}(t) = U_0(t) - \Sigma_j \left(E_{Lj} \cdot \Delta x_{Lj}\right) \qquad (4)$$

3. Leader model parameter analysis

The model parameter analysis was done by modifying input parameters in both Rizk and Lalande leader models to check their influence on the output variables of the long gap discharge simulation like leader tip potential, LCR length, breakdown voltage and breakdown time. The analysis done in our work is based in experimental data reported in [1] of a breakdown event, therefore a detailed study of the $U_{50\%}$ was not considered.

The experimental data used for the analysis was taken from a full discharge streak image in [1], in data pairs of leader tip location and time, as it is shown in Fig. 1. The experimental setup was a 10 m air rod-to-plane electrode arrangement tested with positive switching-like voltage impulses of $U_{\mathrm{cr}} = 1.7$ MV and 500/10000 μs waveshape. The tip of the rod was a 10 mm radius cone. More details of the set-up, test conditions and measuring system can be found in [1].

The leader tip location was used as common data input for both leader models. In the Rizk model the leader length, (understood as the total gap length minus the instantaneous leader tip location) was used directly in (1). In the Lalande model, the leader tip location was discretized into leader segment lengths. Then, these segment lengths were multiplied by a constant charge per unit length q_L in order to obtain charge steps used in (2), i.e. $\Delta Q_{SC} = q_L \cdot \Delta x_L$. The constant q_L represents physically the charge necessary for a unit length advancement of the leader tip [3]. It is also related with tests were switching-like voltage impulses are used, where the leader propagates at an almost constant velocity (ca. 1 cm/μs) and the total current injected was almost constant (ca. 1 A) [1,2]. The procedure followed to estimate the LCR progression for both leader models can be summarized as:

(1) From the experimental data, the spatial location of the leader tip was known during time of the discharge event. The rod electrode potential was a double exponential waveform of $U_{\mathrm{cr}} = 1.7$ MV and waveshape 500/10,000 μs [8].

(2) The estimated potential along the leader was assigned to a tortuous thin leader channel in a three-dimensional electrostatic

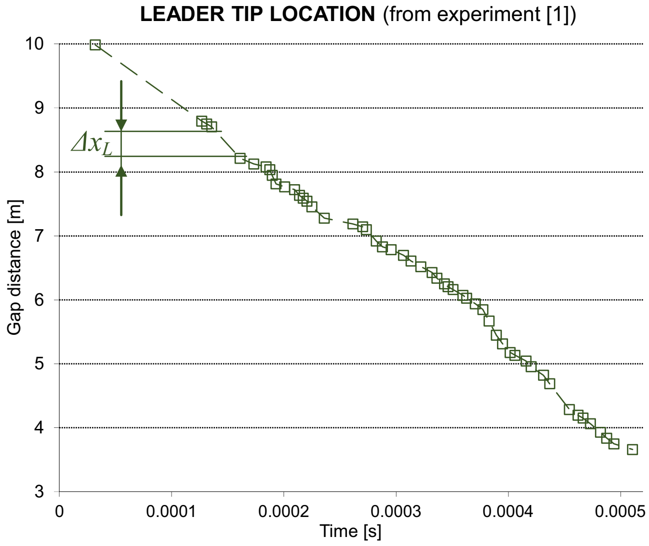

Fig. 1. Leader tip location. Experimental data from a discharge streak image [1].