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The leader propagation velocity in long air gaps

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***Abstract*—Experimental measurements of long gap discharges and its interpretation are the base of engineering equations and complex models to design clearance distances, lightning protection systems, among others. Parameters like leader propagation velocity, average electric field of the leader channel, stability electric field of the streamer region, etc. are derived from experimental measurements for rod-plane arrangements. However, in high voltage engineering geometries are not only rod-plane arrangements but also rounded electrode geometries.**

Experimental measurements of sphere – plane arrangements are presented in this paper. Attention is given to the velocity of propagation of the leader. The velocity of propagation of the leader is compared for two different applied voltage conditions, such as overvoltage and non-overvoltage. Experimental observations indicate that the velocity of the leader does not have a linear relationship with the increment of the applied voltage, as described by other authors for rod-plane arrangements.

By means of a model based on the physics of the discharge, it is observed that the velocity of propagation of the leader depends on the injected charge to the leader channel. The injected charge depends on the background electric field, the potential at the leader tip, the steepness of the applied voltage waveform, among other parameters.

Keywords-breakdown; leader; propagation; modeling; sphere; velocity.

I. Introduction

Several engineering approaches such as lightning protection design and design of external clearances in high voltage stations, among others are based on the understanding of the discharge physics. The physics built to describe the discharge process for positive and negative discharges are a combination of knowledge gained from experimental research work performed by different scientist at Les Renardieres group [1]–[3] and the attempts to model such experiments using the principles of physics [4]–[7]. Two main parts composed the processes of the discharge: the leader channel and the streamer region. Depending on the polarity of the discharge different behavior has been described for the leader and the streamer and its propagation.

Based on the experimental observations various models to predict breakdown, lightning propagation and the leader inception have been put forward. Parameters like the leader velocity, the average electric field of the leader channel or at the streamer region are used as input for such models. However, this input parameters are all derived from experimental measurements to rod-plane arrangements.

In high voltage applications, rounded geometries are used with the aim to reduce the electric field stresses and withstand higher voltages. In order to understand the applicability of the available models, it is necessary to understand experimentally the behavior of discharges on arrangements different than a rod-plane gap.

The following article presents measurements performed for sphere - plane arrangements at different gap distances. Attention is given to test performed under overvoltage conditions vs. non-overvoltage condition. Based on the experimental data, the average speed of the leader is calculated. It is observed that under overvoltage conditions the leader propagation speed increases and it does not behave as reported for rod-plane arrangements. Test results are compared with modeling of the discharge based on principles of physics.

II. Experimental Results

A. Test set-up and procedure

All tests were performed with switching impulse of positive polarity. The applied waveform was a standard waveform of 250/2500 µs rise and fall times, respectively. The voltage level of the 50% breakdown probability, U_{50}, was obtained by using the well-known “up and down procedure” with at least 30 valid voltage applications in each test. During the test, the applied voltage and the waveform of the voltage were recorded. Three digital cameras were used to record the trajectories of the

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discharge and one high speed CCD camera was used to record details of the discharge. All tests were carried indoors in a high voltage hall. All test results presented here have been corrected to the standard reference atmosphere and the corrections were made according to the procedure given in IEC 60060-1[8].

The sphere - plane arrangement was vertically installed with enough distance to the walls of the laboratory, to avoid interference on the breakdown voltage. A cooper sphere with diameter of 0.5 m was used in the test. Distance to floor was variated from 3 m to 9 m. Depending on the gap length the resolution of high video frames, the acquisition speed of the camera (FPS – frames per second) was changed to obtain an optimal result. Figure 1 presents a picture of the experimental set-up.

Figure 1. Breakdown photograph for sphere 0.5 m – plane arrangement under positive switching impulses

After the 50% breakdown voltage was measured, tests under overvoltage conditions were performed. For a gap distance of 5 m, tests at voltages 19%, 34% and 43% higher than the measured U_{50} breakdown voltage were done. 15 impulses for each overvoltage condition were applied.

B. Test results

The test results are summarized in Table I and Figure 2. Table I provides the 50% breakdown voltage at standard atmospheric conditions, U_{50std}, for the different tested gap distances. Figure 2 presents shots of the discharge progress along the gap.

TABLE I. U_{50STD} SPHERE 50 CM – PLANE GAP

Gap distance [m]	U_{50std} [kV]
3	1087
5	1380
7	1635
9	1911

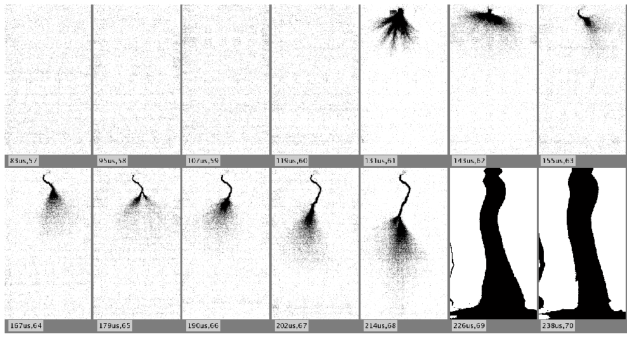

Figure 2. Leader propagation path for 3 m gap distance for 0.5 m diameter sphere– plane arrangement under positive switching impulses. The picture was taken with 84000 FPS and 11.9 µs per frame.

III. LEADER VELOCITY OF PROPAGATION

Prior to each test, the black level of the camera was recalibrated in order to use full dynamic range of the camera sensor. In order to capture low luminous leader propagation, the high-speed camera was operated in such a manner that higher luminous events such as breakdown, or events just before breakdown can saturate the 12-bit monochrome camera sensor.

To carry out further analysis, each frame was normalized in luminosity. After the luminosity normalization, each frame was further processed to find the two-dimensional leader propagation.

A. Leader propagation velocity calculation method

The calculation of the two-dimensional leader speed is divided in two steps. The first step is the pre-determination of the leader propagation path based on the two-dimensional path of the spark after the breakdown. The second step is finding the leader tip position from the time of the first streamer inception to the time of the final jump condition by analysing each frame acquired between these two times. Both step one and two are implemented by first dividing each frame into a number of horizontal rows (based on its vertical resolution) and then finding the mid-point of pixels in each row brighter than a certain threshold. Therefore, the row-number and the mid-point in each row represent the vertical and horizontal position of the leader.

By comparing the leader tip position between two consecutive frames, the instantaneous two-dimensional leader propagation speed could be obtained. Additionally, by taking the moving average of several consecutive frames, a moving-averaged instantaneous two-dimensional leader propagation speed could be found. This moving-averaged result should be considered as more accurate and representative, because it reduces the spikes of calculated speeds.

B. Results

The leader velocity was calculated for all measured cases. The average velocity is summarized in Table II for non-overvoltage cases and in Table III for overvoltage cases for the gap distance of 5 m. The increment of average speed between overvoltage and non-overvoltage is compared in Table III.

TABLE II. LEADER PROPAGATION VELOCITY SPHERE 50 CM – PLANE DIFFERENT GAP DISTANCE

Gap distance [m]	U_{50std} [kV]	Average speed [cm/µs]
3	1087	1.65
5	1380	3.28
7	1635	2.56
9	1911	2.48

TABLE III. OVERVOLTAGE LEADER PROPAGATION VELOCITY

Gap distance [m]	% over U_{50std}	Average speed [cm/µs]	Increment respect to non-overvoltage
5	19	3.9	19%
	34	4.98	51%
	43	6.16	87%

IV. DISCUSSION

The average leader propagation velocity obtained for the sphere – plane arrangements under non-overvoltage conditions varies from 1.65 to 3.28 cm/µs. Measurements reported in the literature [1] for rod – plane arrangements are of the order of 1 to 2 cm/µs.

The leader velocity under overvoltage conditions for sphere-plane tests summarized in Table III; indicate that under overvoltage conditions, the increment of the leader speed is not linear with the increment of the applied voltage.

Similar studies performed by Diaz et al [9] for rod-plane arrangements under overvoltage conditions. The authors reported leader propagation velocities of 8.5 and 9.4 cm/µs for gap distances of 8 and 7 m, respectively, for voltages 30% higher than the U_{50std} of the arrangement. These leader velocities are much higher than the 30% of the maximum average velocity reported for rod-plane arrangements in [1].

Experimental measurements of the leader velocity for rod-plane gap arrangements presented in [1] ensure that the average leader propagation velocity remains almost constant for positive switching impulses, increasing linearly with the applied voltage, independently of the gap length. However, experimental results presented in this manuscript summarized in Tables II and III disregard such hypothesis for arrangements sphere-plane type, as the leader propagation velocity does not increases linearly with the increment of the applied voltage.

Based on the experimental results, it is possible to presume that the leader propagation speed is affected by the background electric field and its variation in time. In order to describe the laboratory measurements from the discharge physics point of view, a model that uses the physics of the discharge is used to reproduce two cases: one for an overvoltage condition 34% higher than the U_{50std} and one non-overvoltage condition, i.e. at the U_{50std} voltage magnitude.

A. Model description

The model developed by Arevalo et al [10], [11] utilizes the physics of the discharge to study the breakdown of high voltage electrodes under positive switching impulses. The main steps that are included in the model are:

- Formation of the streamer corona discharge at the tip of the high voltage electrode.
- Transformation of the stem of the streamer into thermalized leader channel, called "unstable leader inception"
- Extension of the positive leader and its self-sustained propagation, called "stable leader inception"

The calculation starts with the evaluation of the background electric field, which depends on the voltage source and geometry of the arrangement. Then, the continuity equations of different particle densities are solved combined with Poisson's equation. The electric current produced by the particle movement is calculated and the gas temperature is evaluated by means of the energy balance equations. If the gas temperature is equal or higher than 1500 K [6], [12], [13], then the streamer-to-leader transition occurs and a leader channel is considered as incepted.

If the condition for "unstable leader inception" is fulfilled an iterative analysis of the leader propagation starts with a determined initial leader length of $L_l(t_0)$ as input. The extension of the leader and the switching impulse voltage source change the potential distribution. The streamer charge generated during the extension of the leader is calculated following Arevalo approximation [14]. The drop of potential along the leader channel $U_{tip}^{(i)}$ during the current simulation step i is evaluated with the equation derived by Rizk [15]:

$$U_{tip}^{(i)} = L_l \cdot E_\infty + x_0 \cdot E_\infty \cdot \ln\left(\frac{Esc}{E_\infty} - \frac{Esc - E_\infty}{E_\infty} \cdot e^{-\frac{L_l(t)}{x_0}} \right) \tag{1}$$

Rizk's equation established that the voltage at the tip of the leader is a function of the leader length L_l, the electric field in the streamer zone E_{sc}, the final quasi-stationary leader gradient E_∞ and the relation x_0, which is the relation between the leader velocity v and the leader time constant Θ

Once the charge in the streamer region has been calculated, the advance of the leader dl'_l can be determined by integrating the velocity of the leader.

$$dl'_L = \frac{\Delta Q_{total}^{(t)}}{q_L} \tag{2}$$

where q_L is the charge per unit length required to transform the streamer located in the active region in front of the already formed leader channel into a new leader segment. The magnitude of q_L is based on the measurements made by Les Renardieres' Group [1].

To represent the tortuous characteristic of the discharge channel a Gaussian distribution based on experimental measurements is used as proposed by Arevalo et al [16].

The calculation finalizes when the streamer region reaches the ground point or when the leader channel stops its propagation.

B. Modeling results

The model was applied to the 5 m gap test for one single shot under overvoltage condition at 34% over the U_{50std} value and one single shot at U_{50std} voltage. Characteristics of applied voltage, geometry, ambient conditions, among others were taken from the test. Magnitudes of the injected charge to the leader channel and leader propagation velocity were calculated and compared with experimental results.

Figure 3 illustrates the simulated leader velocity and the experimental data. Good accuracy is obtained between simulation and measurements for both the overvoltage and the non-overvoltage conditions. Similar trends for the leader velocity are observed. Note that for the simulated cases an earlier stage of the propagation of the discharge is obtained, which is not visible for the high-speed camera as it is not part of a luminous event.

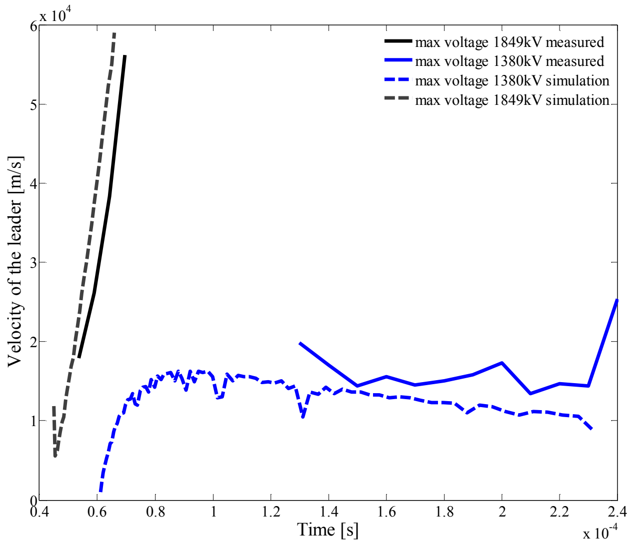

Figure 3. Leader propagation velocity for overvoltage and non-overvoltage condition.

It is clearly observed the leader inception, propagation and the breakdown occur faster when the arrangement is subjected to a higher peak voltage of the applied switching impulse, i.e. steep *dV/dt*. It is important to outline that the rise and fall times of the impulse waveform are the same for both calculated cases.

One of the key parameters that determines the velocity of propagation of the leader and its length is the charge injected to the leader channel. Figure 4 illustrates the total charge required for the leader propagation.

The figure shows that a greater amount of charge is injected into the leader channel in shorter time elapse for the case of higher voltage application compared with the case of non-overvoltage. In addition, it is observed that the charge is injected faster and more continuously for the overvoltage application. Consequently, it takes longer time for the leader to propagate in the case when non-overvoltage is applied.

As previously mentioned, the velocity of the leader depends on the amount of charge that it is injected into the channel. The charge injected in the leader channel corresponds to the charge generated in the streamer region. The charge of the streamer region, in turn, depends on the background electric field and the potential at the tip of the leader channel.

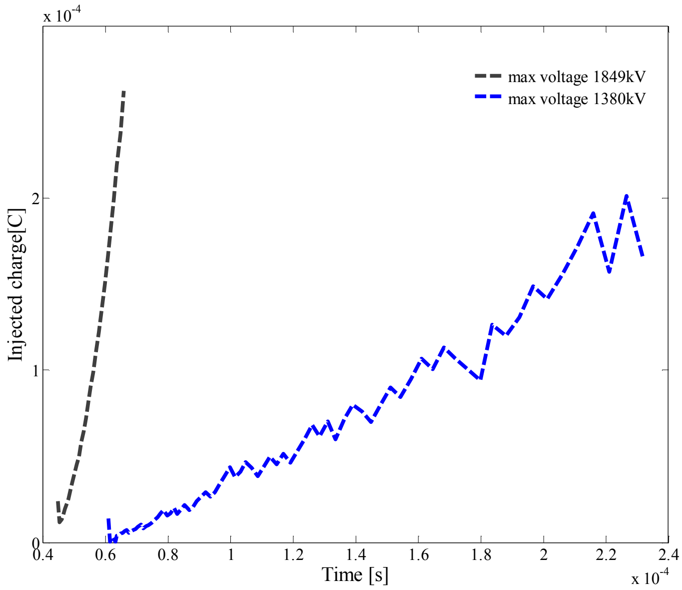

Figure 4. Injected charge to the leader channel.

V. Conclusions

Experimental measurements of the leader propagation velocity for sphere – plane arrangements under overvoltage and non-overvoltage conditions are presented in this paper.

Experimental results indicate that the velocity of the leader for sphere-plane arrangement at non-overvoltage condition is between 1.65 to 3.28 cm/µs, which it is different from the range reported in the literature for rod-plane arrangements. Additionally, the tests under overvoltage conditions show that the leader velocity does not increase linearly with the applied voltage as it was reported for rod-plane arrangements.

Numerical modeling of tests with overvoltage and non-overvoltage conditions indicate that the leader propagation velocity is affected by the charge injected from the streamer region. The streamer charge is affected by the background electric field, the steepness of the applied switching impulse, among other parameters.

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