Long gap breakdown calculation method considering competitive discharges

L. AREVALO[1*] and D. WU[1]
[1]ABB Power Systems, HVDC, Ludvika, Sweden
*Email: Liliana.Arevalo@se.abb.com

Abstract: A model based on the physics of the discharge is utilized to study the effect of competitive leader discharges incepted in arrangements rod – plane gap type. Results indicate that leaders can be incepted from the competitive gaps; however, a slight advantage on the background electric field will help that only one leader succeed in completing the final jump. Results of leader speed, current and propagation path indicates that the effect of competition between multiple leaders is to delay the breakdown process.

1. INTRODUCTION

A numerical model based on the physics of the discharge of long spark gaps should take into account the inception and development of streamers from the high voltage electrode, subsequent streamer to leader transition, inception of a stable leader, propagation and the final jump. In general, depending on the distance of the grounding planes several streamers can be generated from different parts of the high voltage electrode. These leaders deposit charge on their path and this charge modifies the background electric field. The change in the background electric field affects the growth and propagation of leaders.

Several engineering and physical models [1 - 4] have been put forward to describe the breakdown voltage of typical high voltage arrangements, e.g., rod - plane, conductor - plane, rod - rod, etc. However none of these models focus on the effect of competitive discharges. In this paper, the competitive effect of discharges from a rod – plane arrangement, propagating towards two grounded planes, e.g., floor and wall is investigated.

2. METHODOLOGY

The developed model by Arevalo et al [5] utilized the physics of the discharge to study the breakdown of high voltage electrodes under positive switching impulses. The model can be used to analyze the effect of multiple connecting discharges from high voltage electrodes. 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 “unstable leader inception”
- Extension of the positive leader and its self-sustained propagation, called “stable leader inception”

2.1 Streamer criteria

Once the high voltage electrode is stimulated by a switching impulse voltage, the background electric field produced by the voltage source is evaluated and the well-known streamer criterion is calculated [6].

If the first streamer corona is incepted, the charge is calculated using the simplified electrostatic approach proposed by Arevalo et al. [7], which assumes that the corona streamer zone is characterized by a constant electric field. If the total charge of the streamer corona is equal or higher than 1µC [6, 8], it is accepted that the transition from streamer to leader takes place.

If the streamer inception criterion is fulfilled in one of the corners of the tip, the leader inception procedure is initiated. However, since the electric field on the arrangement is constantly modified by the change of the voltage source, the streamer inception criterion is continuously analyzed for the arrangement. If another point over the high voltage electrode satisfies the inception of streamers the analysis of this criterion will be stopped (since this study will focus on only two connecting leaders) and the investigation will concentrate on the inception of leaders of the two incepted corners.

2.2 Stable leader inception

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 as presented in section 2.1 and in [5, 7] but now including both leaders and its streamer regions. This is facilitated by representing the drop of potential along the leader channel $U_{tip}^{(i)}$ during the current simulation step i with the equation derived by Rizk [1]:

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

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.

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

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 this q_L is based on the measurements made by Les Renardieres' Group [9] and the value used by numerical models [5, 8, 10]; it is listed in Table 1.

Table 1: Input parameters for the numerical simulation.

Parameters	Magnitude	Description
q_l [C/m]	45 x 10^{-6}	Charge per unit length to sustain a leader channel
E_∞ [kV/m]	30	Final quasi-stationary leader gradient
L_{L0}[m]	2 x 10^{-2}	Initial leader length
E_{sc}[kV/m]	450	Stable electric field inside the streamer region
x_0[m]	0.75	Constant given by the ascending positive leader speed and the leader time constant

Once the leader is incepted the condition necessary for its stable propagation is analysed, as described above. The new length of the leader segment L of the time $(t + dt)$ can be calculated following equation (1) and (2). The propagation condition depends on the background electric field as well as the rate of change of the electric field. In the calculation the leader discharge is assumed to take a straight and vertical path to ground planes.

The calculation finalizes when the streamer corona region reaches the ground point or when the leader channel stops its propagation. For calculation of the electric field at different conditions finite element method software is used.

3. APPLICATION OF THE METHODOLOGY

The procedure was applied to an arrangement composed by a square rod and two grounded planes. The rod characteristics are side length 2 cm and 6 m long rod. The rod faced two closer grounding planes, the floor and one wall located from the tip of the rod at 10 m and 10.5 m, respectively. The rest of the distances as ceiling, and other walls are considered as infinite boundaries to avoid its effect on the background electric field calculation.

The rod was excited with a standard positive switching impulse of maximum voltage of 2500 kV, 250/2500 µs.

The path of the discharge was assumed as non-tortuous, i.e. a straight line, one path vertical towards the floor and the other horizontal towards the wall.

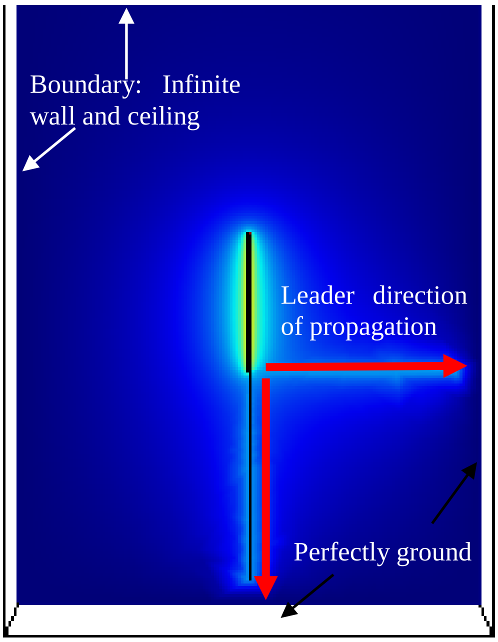

Figure 1: Simulated set – up. The red arrows indicate the selected path of propagation of the discharge and the white and black arrows show the boundary conditions used in FEM software.

To be able to compare the effect of the competitive leaders the breakdown voltage, speed of the leader and extension of the leader channel issued from both leader discharges are obtained. Furthermore, the comparison of breakdown voltages where either the leader towards the wall or the floor is absent (i.e. only one leader is developed) are also calculated.

Table 2: Inception and breakdown voltage

Streamer inception voltage[kV]	Breakdown voltage [kV]	Leader direction
189 kV	2040 kV	To floor
300 kV	-	To wall
210 kV	1850 kV	To floor only one leader – all walls at infinite distance

Table 2 indicates the streamer inception voltage of the competitive arrangement. It is observed that the streamer inception occurs at lower voltage towards floor than towards wall, giving advantage to the discharge process to floor. In addition, notice that the breakdown voltage without competitive gaps happens at lower voltage level than the case with competitive discharges. As the distance between both leaders differs on only 0.5 m, the two leaders compete efficiently with each other, as it is shown in Figures 2 and 3. The competition between the two leaders delays the breakdown process and consequently the breakdown voltage is higher for the competitive gaps arrangement than the breakdown voltage without competitive gaps.

Figure 2 shows the leader speed associated with the leaders towards wall and floor. Observe that the speed of the leader towards floor grows exponentially until the final jump condition is reached whereas the speed from the other leader towards wall increases initially but reduces its speed as the leader towards the floor takes over. After several unsuccessful attempts (unstable leader inception) the leader towards wall cannot increase its speed and it is almost aborted. Meanwhile, as the leader towards floor comes closer to the ground plane, it starts to grow rapidly. In accordance with this, the growth of leader towards wall is arrested and aborted.

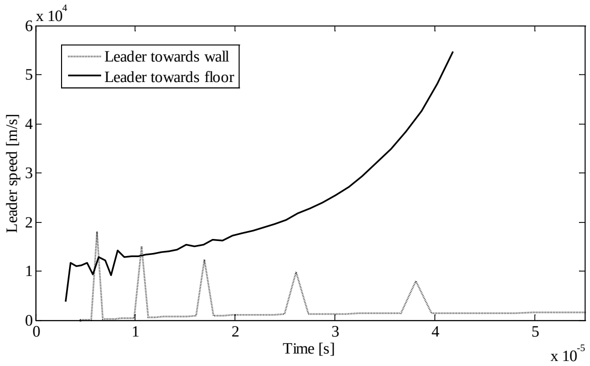

Figure 2: Speed of the leaders propagating from the high voltage electrode vs. time. Continuous line corresponds to the leader propagating towards floor and the dotted line corresponds to the leader propagating towards wall.

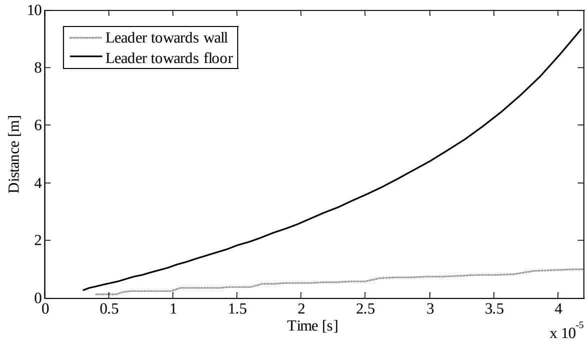

Figure 3: Distance of the leaders propagating from the high voltage electrode vs. time. Continuous line corresponds to the leader propagating towards floor and the dotted line corresponds to the leader propagating towards wall.

Figure 3 illustrates the path of the leaders towards wall and floor until final jump condition is reached. Note that the extension of the leader towards wall is smaller compared to that from the leader towards floor. Once the leader towards floor has reached the final jump condition, the leader to wall had just advanced 1 m of the length of the gap of 10.5 m.

This evince that the moment one leader starts accelerating towards the ground plane, the growth of the other leader will be arrested. The reason for this is that the charge deposited in space by accelerating leader reduces the electric field in the vicinity of other leaders impeding their motion.

4. CONCLUSIONS

In this paper it is simulated the breakdown process of two competitive gaps. The results show that the propagation characteristics of the leaders are influenced significantly by the presence of other leaders. A slight advantage from the background electric field is enough for one connecting leader to take over forcing the other connecting leaders to reduce its speed of propagation and abort.

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