Journal of Electrostatics 68 (2010) 439–444

Contents lists available at ScienceDirect

Journal of Electrostatics

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

Significant parameters affecting a lightning stroke to a horizontal conductor

Mohamed Nayel [a,*], Zhao Jie [b], Jinliang He [c]

[a] Assiut University, Assiut 71516, Egypt
[b] China Southern Power Grid, Guangzhou, 510623, China
[c] Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 23 August 2009
Accepted 7 June 2010
Available online 25 June 2010

Keywords:
Air gaps
Charge simulation method
Conductors
Electric breakdown
Lightning
Striking distance

ABSTRACT

This paper studies different parameters affecting a lightning stroke to a horizontal conductor. An electromagnetic model has been constructed to consider the influences of different lightning and horizontal conductor parameters and ambient conditions on the lateral striking distance. The results show that lightning leader parameters, horizontal conductor voltage, horizontal conductor height, and ground slope have a series effect on the lateral striking distance. Based on the results, recommendations are made to decrease the lightning stroke to the horizontal conductor.

1. Introduction

There is a long history of field observations into the attractive effect of lightning and several empirical rules for determining the protection zone of a free standing structure have long been proposed. Several attempts have been made to analytically determine the striking distance of a horizontal conductor [1].

Golde assumed that the initiation of upward streamers from a grounded object is a striking signal [2,3]. Then he assumed that an upward leader appears in a long nonuniform gap when the average electric field in the gap exceeds a critical value. The average electric field was defined as the ratio between the downward leader tip voltage and the gap length. Golde assumed that the critical breakdown electric field between the downward leader tip and either a ground plane, a grounded vertical conductor, or a grounded horizontal conductor will be same. This critical electric field is 500 kV/m for a negative stroke and 300 kV/m for a positive stroke [4,5].

Others assumed an air gap with a constant length around the horizontal conductor. If the potential difference of the air gap exceeds its critical breakdown voltage, then an upward leader will incept from the conductor [6].

Chowdhuri had assumed empirical equations for critical breakdown voltages for the rod conductor gap based on experimental results [7]. The critical positive-polarity breakdown voltage V_{clp} is as follows:

$$\begin{aligned} V_{\mathrm{clp}} &= \tfrac{3400}{1+8/D} k_{\mathrm{gp}} \ \ (\mathrm{kV}) \quad (\text{for } D < 15\ \mathrm{m}) \\ V_{\mathrm{clp}} &= (1400 + 55D) k_{\mathrm{gp}} \ \ (\mathrm{kV}) \quad (\text{for } D > 15\ \mathrm{m}), \end{aligned} \tag{1}$$

where D is gap length in m, k_{gp} is the conductor-rod gap factor for positive-polarity breakdown voltage.

The critical negative polarity breakdown voltage V_{cln} is as follows:

$$\begin{aligned} V_{\mathrm{cln}} &= \left(1180 D^{0.45}\right) k_{\mathrm{gn}} \ \ (\mathrm{kV}) \quad (\text{for } D < 15\ \mathrm{m}) \\ V_{\mathrm{cln}} &= 1.8(1400 + 55D) k_{\mathrm{gn}} \ \ (\mathrm{kV}) \quad (\text{for } D > 15\ \mathrm{m}), \end{aligned} \tag{2}$$

where k_{gn} is the conductor-rod gap factor for negative polarity breakdown voltage.

Based on the knowledge of the physics of the discharge [8–11], Garbagnati developed an empirical approach. The approach is based on the idea that a substantial similarity exists between lightning phenomena and discharges in large air gaps. The proposed model takes care of the discharge physics basics, mainly the propagation of the inception and propagation of upward leaders from earthed structures [12].

Rizk had introduced another model for assessing the exposure of free standing structures and horizontal conductors [13]. He proposed a formula to estimate the induced potential necessary for

* Corresponding author.
E-mail addresses: mnayel@aun.edu.eg (M. Nayel), zhaojie@csg.cn (Z. Jie), hejl@tsinghua.edu.cn (J. He).

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doi:10.1016/j.elstat.2010.06.005

continuous positive leader inception. The induced voltage V_c for a vertical free standing structure of height d is

$$V_c = \frac{1556}{1+\frac{3.89}{d}}. \quad (3)$$

The induced voltage for the horizontal conductor V_c with radius a and at height d is

$$V_c = \frac{2247}{1+\frac{5.15-5.49\ln(a)}{d\,\ln(\frac{2d}{a})}}. \quad (4)$$

In other works, it was assumed in studying Franklin rods that, an initiatory electron starts at the boundary of the ionization zone, creating an electron avalanche on its way toward the Franklin rod. This primary avalanche where the electrons are populated at the head, leaves behind positive ions in the wake of the avalanche. The electrons of the primary avalanche accelerate under the resultant field induced by the downward leader, and the field resulting from the avalanche produced positive space charge. A number of positive ions N_{+1} are lifted behind by the primary avalanche. The criterion for the primary avalanche to streamer transition is that the total number of positive ions created by the successor avalanches N_{+2} forming the second generation is equal to the number of positive ions N_{+1} of the primary avalanche. This will ensure that the discharge process becomes self sustained [14,15].

The voltage condition proposed by Rizk for a lightning stroke to the horizontal conductor has been modified to consider the horizontal conductor voltage, humidity, and air density. The downward lightning leader is modelled by exponential charge decay. The parameters affecting lightning striking distance are summarized into three main categories: lightning parameters, conductor parameters, and ambient condition parameters (weather and ground slope). The different parameters affecting lightning striking distance for a horizontal conductor have been studied.

2. Electromagnetic model

Consider a horizontal conductor at height d exposed to a downward lightning leader, as shown in Fig. 1. An electromagnetic model has been constructed to study the lightning stroke to the horizontal conductor. It is assumed that, the downward lightning leader pass from the cloud to the ground does not affected by the presence of the grounded horizontal conductors till it reaches lightning striking distance far from the horizontal conductor [1–16].

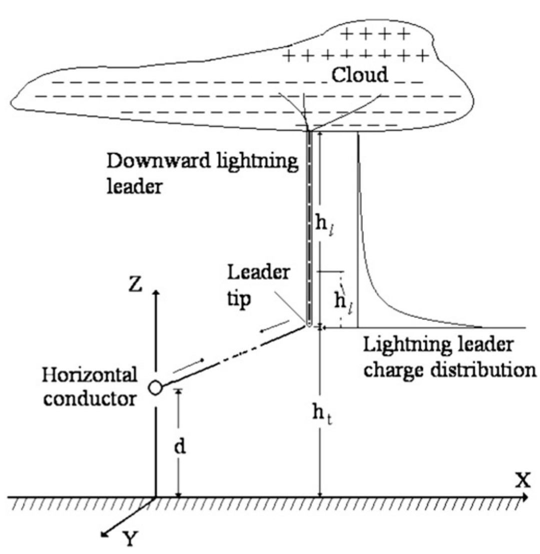

Fig. 1. Schematic arrangement of a horizontal conductor struck by the downward lightning leader.

The charge distribution inside the downward lightning leader is very complicated. The charge density is the highest at the level of the lightning leader tip and decreases with the lightning leader height. Different charge distributions inside the lightning leader, such as an exponential decay of the charge density, a combination between point charge at the leader tip and constant line charge, and a combination between point charge at the leader tip and linear charge decay, were assumed in previous works and a comparison between these different charge distributions has been studied before [16] and showed that the exponential decay is more accurate.

In this paper, the charge decaying distribution along the stepped leader is assumed to be exponential of negative charge and given by

$$\rho\left(h_l^{\grave{}}\right) = -\rho_s e^{-\alpha h_l^{\grave{}}}, \quad \alpha = \frac{\ln(\rho_c/\rho_s)}{(h_l)}, \quad (5)$$

where ρ_s is the charge density in C/m at the downward leader tip ($z = h_t$), ρ_c is the charge density in C/m at the cloud base ($z = h_c$), $h_l^{\grave{}} = z - h_t$ and h_l is the downward lightning leader length in m.

For the most studied cases, the downward lightning leader length h_l is assumed to be constant and equal to 3 km and $\rho_c/\rho_s = 0.05$. This value results in $\alpha = 10^{-3}$. The relation between the return stroked current and the total charge of the lightning stroke is studied before [17,18]. The return stroked current speed in this paper is assumed to be 0.3 times the light speed. The downward lightning leader is simulated by N_ℓ discrete line charges along the positive X, Y, Z directions. The charge density $\rho_{n\ell}$ for the n_ℓ segment will be as follows:

$$\rho_{n\ell} = \frac{\rho_s e^{\alpha h_s}}{-\alpha h_l/N_\ell}\left(e^{-\alpha\left(h_t+h_l\frac{n_\ell-1}{N_\ell}\right)} - e^{-\alpha\left(h_t+h_l\frac{n_\ell}{N_\ell}\right)}\right). \quad (6)$$

The potential of the downward lightning leader V_ℓ at any point in space is expressed as:

$$V_\ell = \sum_{n\ell=1}^{N_\ell} \rho_{n\ell}\left(P_{n\ell} - P_{n\ell}^{\grave{}}\right), \quad (7)$$

where $P_{n\ell}$, $P_{n\ell}^{\grave{}}$ are the potential coefficients for n_ℓth discrete constant charge density and its image due to the ground effect (see Appendix I).

The formula proposed by Rizk [13] to estimate the voltage at the centre of the horizontal conductor due to the presence of the lightning leader is chosen to be the basis for investigating the lightning stroke to the horizontal conductor. The effect of air density on leader inception and sparkover of the long air gap was developed by Rizk [19]:

$$V_c = \frac{2247}{1+\frac{5.15-5.49\ln(a)}{\delta k d\,\ln(\frac{2d}{a})}}, \quad (8)$$

where δ is the relative air density.

The streamer gradient E_s is approximately proportional to the relative air density δ:

$$E_s = E_{s0}\delta, \quad (9)$$

where E_{s0} is the streamer propagation field at sea level.

In [20], the streamer propagation field varies linearly with higher altitudes, thus,

$$E_s = E_{s0}\delta K, \quad (10)$$

where $K = 1 + (h - h_0)/100$, h_0 is the standard value of 11 g/m^3, and h is the absolute humidity in g/m^3.

Geldenhuys [21] has developed an empirical positive streamer model for positive switching impulses:

$$E_s = E_{s0}\left[\delta^{1.2} + 1.3\delta^{-0.17}(h-11)/100\right]. \quad (11)$$