INTERNATIONAL CONFERENCE ON LIGHTNING PROTECTION
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

The mesh method in lightning protection analyzed from a lightning attachment model

L. Arevalo
R&D Department
ABB Power Systems HVDC
Ludvika, Sweden
Liliana.Arevalo@se.abb.com

V. Cooray
Division of electricity
Uppsala University
Uppsala, Sweden
Vernon.Cooray@angstrom.uu.se

***Abstract*—Based on the well-known rolling sphere method, international standards recommend the location of the external lightning protection system of structures. The design of the external lightning protection system of structures of height of less than 60 m can be done by installing a mesh on top of a roof of the structure or by creating a mesh with wires at certain distance from the roof of the structure. The prospective downward leader current that the mesh can incept depends on the size of the mesh and the current magnitude is given as recommendation in the international standards. This paper analyses the relation prospective negative downward leader current vs. mesh size from a lightning attachment model. The model is applied to a perfectly grounded structure with maximum height of 50 m protected by two different external lightning protection systems recommended by the international standards. The results showed difference on magnitude of the prospective downward leader current the standards recommend and the ones obtained using the lightning attachment model for meshes of shorter size. Discrepancies concerning the minimum downward leader current that can be incepted by a mesh made by wires located at certain distance from the ground structure and a mesh located on top of the building are obtained.**

Keywords-downward leader, lightning protection; lightning attachment; mesh; upward leader.

I. INTRODUCTION

The design of the external lightning protection of grounded structures is based on the empirical method known as the rolling sphere method. Because of its easy application and understanding, the rolling sphere method is worldwide used for the design of the external lightning protection of structures. The method determines the minimum downward leader current an external lightning protection system can incept. Based on the rolling sphere method, different protection techniques have been derived and are recommended in the international standards.

International standards as IEC 62305[1] provide a guideline about how lightning protection of structures shall be performed. For structures of height less than 60 m, the standard proposes two different methods of protection one is the volume protected by wires combined in a mesh and the other the mesh work.

The protection by wires consists on the installation of wires combined in a mesh on the roof of the structure. The meshed wires are located at a certain height respect to the grounded object. The size of the mesh is determined by the rolling sphere method depending on the lightning protection level of the structure, as it is indicated in the standard [1] and Table I.

The mesh method consists on the installation of a mesh network on top of the roof of the structure. The dimensions of the mesh shall not be greater than the values specified in IEC 62305. The network is constructed in such a way that lightning current will always encounter at least two distinct metal routes to earth. Details of the mesh method can be found on [1, 2]

The first three columns of Table I specify the size of the mesh and the minimum downward leader current that may terminate on the structure when using this mesh size for different lightning protection levels. For the volume protection by wires the separation between the mesh and the grounded structure should be larger than a critical value and this critical value is also given in Table I.

TABLE I. IEC 62305[1] RECOMMENDED SIZE OF THE MESH

LPS	Mesh	I [kA]	Critical height of the mesh for protection with wires
I	5 x 5	3	0.15
II	10 x 10	5	0.42
III	15 x 15	10	0.63
IV	20 x 20	15	0.84

The aim of this paper is to study the effectiveness of mesh on top of the structure and the mesh formed by wires in structures of height less than 60 m and its corresponding protection level as specified by the international standard IEC62305. The method of protection called “volume protected by wires combined in a mesh” was already studied in [3] using a lightning attachment methodology similar to the one presented in this paper.

II. METHODOLOGY

The model utilizes the physics of the discharge to study the lightning attachment to grounded structures. The model has been well validated in literature [3–6]. The model only considers the case of positive upward leaders incepted due to a downward leader of negative polarity. The main steps included in the model are:

- Formation of the streamer corona discharge at the grounded object (first and second corona inception).
- Transformation of the stem of the streamer into thermalized leader channel “unstable leader inception”
- Extension of the positive leader and its propagation, called “stable leader inception”

Only description of new features added to the model used in previous studies will be added in this paper. More information about the complete upward leader inception process can be found in other publications of the authors[3]–[5], [7]–[9]. In Figure 1, the flow diagram of the complete lightning attachment process is presented; the two new parts of the calculation are highlighted: glow corona and streamer to leader transition.

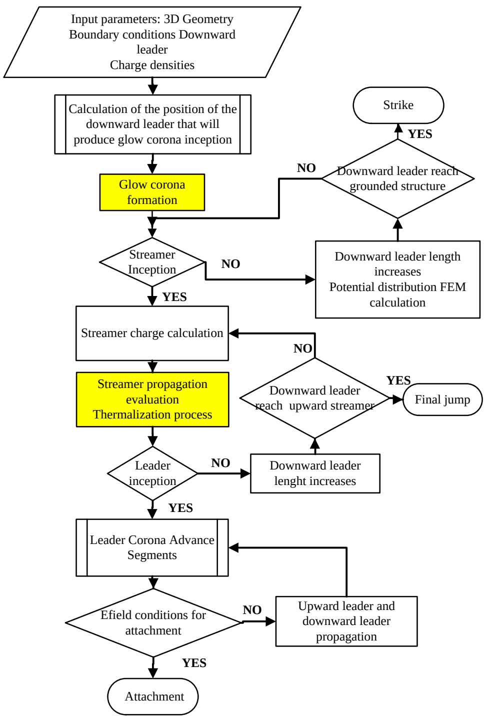

Figure 1. Flow chart for lightning attachment process of positive upward leaders. Noticed that highlight in the yellow color can be found the two new processes added to the model

A. *Glow-corona formation*

For the principal behavior of the streamer is assumed that the stem is composed by three kinds of particles: electrons, ions and neutral particles, as presented in[4].

The model solves Poisson’s equation simultaneously with the continuity equations including the effects of ionization, attachment, recombination and photoionization. Under these conditions, the system of continuity equations for densities of electrons, positive and negative ions is written in the following manner:

$$\frac{\partial N_e}{\partial t} = S + N_e \alpha |W_e| - N_e \eta |W_e| - N_e N_p \beta - \frac{\partial (N_e W_e)}{\partial x} + \frac{\partial}{\partial x}\left(D \frac{\partial N_e}{\partial x} \right) \tag{1}$$

$$\frac{\partial N_p}{\partial t} = S + N_e \alpha |W_e| - N_e N_p \beta - N_n N_p \beta - \frac{\partial (N_p W_p)}{\partial x} \tag{2}$$

$$\frac{\partial N_n}{\partial t} = N_e \eta |W_e| - N_n N_p \beta - \frac{\partial (N_n W_n)}{\partial x} \tag{3}$$

$$\frac{\partial N_m^i}{\partial t} = \delta^i W_e N_e - \frac{N_m^i}{\tau_m^i} \tag{4}$$

Where t is time, x the distance from the anode; N_e, N_p, N_n and N_m, are the respective electron, positive ion, negative ion, neutral particles and molecule densities; and W_e, W_p and W_n the respective electron, positive ion and negative ion drift velocities. The superscript i denotes the *ith* excitation coefficient of a molecule level and also photons emitted from that level. δ_i is the excitation coefficient level, μ_i and τ_{mi} are the respective photons absorption coefficient and the excited molecule lifetime from that level . The symbols α, η, β, and D denote the ionization, attachment, recombination and electron diffusion coefficients respectively, and S is the source term due to photoionization. All coefficients in the system of equations (1) to (4) are functions of the local electric field strength [10]. When the local electrical field is modified by space charge, the coefficients in the above equations become space and time dependent.

B. *Streamer – leader transition*[11]

The model for streamer to leader transition presented on [11] is used. The model is built on three basic principles of the thermo-dynamical mechanism proposed by Gallimberti [12]: the gas temperature increases by Joule effect, the axial variations along the channel are negligible in comparison to the radial ones, the current of a propagating leader is produced in the streamer zone and injected in the leader head, and therefore it is an external parameter for this region, the inception condition of the leader is attained if the gas temperature reaches a critical temperature T_{cr} of ~1500 K, considering the stem as a cylindrical plasma channel, the gas temperature can be calculated using the following equations [12]:

$$\frac{d\left(\frac{7}{2}kT_h N_h \pi a^2\right)}{dt} = \left(f_e + f_t + f_r\right)\cdot EI + \frac{W_v(T_v) - W_h(T_h)}{\tau_{vt}} \quad (5)$$

k is boltzman constant, N_n is the density of neutral particles of ambient air, *a* radius of the stem, T_h and T_v are translational and vibrational temperature of neutrals, W_v is vibrational energy per unit length f_t, f_r, f_e, f_v are partition coefficients for translational energy, rotational energy, electronic excitation energy and vibrational energy, τ_{vt} is equivalent time constant for relaxation of the vibrational energy into translational form, depends on gas temperature and humidity, *E* is mean electric field in the stem, *I* is the current entering from the streamer region into the stem. By integration of equation (5), is possible to calculate the minimum streamer charge necessary for the stem to be heated above the critical temperature and for the leader channel to be launched.

C. Stable upward 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 upward leader and the distribution of the charge along the stepped leader channel change the potential distribution. The drop of potential along the upward leader channel $U_{tip}^{(i)}$ during the simulation step *i* is calculated with the equation derived by Rizk [13]:

$$U_{tip}^{(i)} = L_l \cdot E_\infty + x_0 \cdot E_\infty \cdot \ln\left(\frac{Esc}{E_\infty} - \frac{Esc - E_\infty}{E_\infty}\cdot e^{-\frac{L_l(t)}{x_0}}\right) \quad (6)$$

Rizk's equation established that the voltage at the tip of the upward leader is a function of the leader length L_l, the electric field in the streamer zone *Esc*, 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.

$$dl'_L = \frac{\Delta Q_{total}^{(t)}}{q_L} \quad (7)$$

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 [14] and the value used by numerical models [12-14]; it is listed in Table II.

TABLE II. 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

Each new length of the leader segment *L* at time *(t + dt)* can be calculated following equation (9) and (10). 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.

D. Distribution of charge along the stepped leader channel

Based on the charge transported to ground by first return strokes, as measured by Berger et al. [15], Cooray et al [16] developed an equation that describes the distribution of charge along the stepped leader channel as it propagates towards ground. According to this study the linear charge distribution along the leader channel is given by,

$$\rho(z) = 8\cdot 10^{-6}\cdot\left(1 - \frac{\xi}{H - z_0}\right)\cdot G(z_0)\cdot I_p + \frac{a + b\cdot\xi}{1 + c\cdot\xi + d\cdot\xi^2}\cdot H(z_0)\cdot I_p \ \text{[C/m]} \quad (8)$$

$$G(z_0) = 1 - \left(\frac{z_0}{H}\right) \quad (9)$$

$$H(z_0) = 0.3\cdot e^{-\frac{z_0}{50}} + 0.7\cdot e^{-\frac{z_0}{2500}} \quad (10)$$

$$\xi = z - z_0 \quad (11)$$

where Z_0 is the height of the leader tip above ground in meters, *H* is the height of the cloud in meters (assumed equal to 4000m), I_p is the return stroke peak current, a = 7.2·10^{-5}, b = 5.297·10^{-5}, c = 1.316 and d = 1.492·10^{-2}. This charge distribution is used here to evaluate the temporal variation of the electric field at the structure as the negative downward leader approaches it.

III. APPLICATION OF THE MODEL

For the analysis, the mesh is assumed to be located on top of a building of 50 m height, with flat roof of 50 x 50 m area. The building is considered as a perfect conductor, the diameter of the conductors of the mesh was assumed to be 1.0 x 10^{-2} m.

In the analysis the axis of the downward leader is located directly at the center of a cell which is located at the center of the mesh. As the downward leader approaches the grounded structure the electric field at the mesh continues increasing and when it reaches a critical value a connecting leader or streamer corona discharge activity is initiated from the mesh.

In order to check whether the downward leader will get attached to the upward leader or upward streamer corona (i.e. the flash is intercepted by the mesh) or to the ground plane (i.e the downward leader penetrated the mesh) the following condition is used: (a) If the corona streamers of the upward leader approach the downward coming leader to such a distance where the background electric field generated by the downward leader is 500 kV/m, it is assumed to be a sufficient criterion for the interception of the downward leader by the upward leader. (b) If the electric field at the ground plane just below the downward leader reaches a value 10^6 V/m or more after taking into account the screening by the mesh, it is assumed to be a sufficient condition for the downward leader to terminate on the ground plane. (c) If the electric field at ground is less than 10^6 but greater than $7.5x10^5$ V/m when the condition (a) is satisfied, it is considered as probable attachment to grid. (d) If the electric field at ground level is less than $7.5x10^5$ V/m when the condition (a) is satisfied the case is regarded as a definitive attachment to ground.

Table III summarizes the results obtained in the calculations for grounded structure protected with mesh formed by wires. The results are given for 5x5, 10x10, 15x15 and 20x20 m mesh dimensions. The heights of these meshes above the ground plane are 0.3, 0.5, 0.7 and 0.9 m, respectively.

TABLE III. LIGHTNING CURRENT INCEPTION ON VOLUME PROTECTED BY WIRES COMBINED IN A MESH

Class LPS	**Wires combined in a mesh**		
	Mesh size[m]	***Return stroke current [kA]***	***Results***
I	5x5	2	Attachment to ground
		3	Probable attachment to mesh
		4	Attachment to mesh
II	10x10	5	Condition for attachment to ground and to the grid are fulfilled almost simultaneously
		6	Probable attachment to mesh
		7.5	Attachment to mesh
III	15 x 15	9	Condition for attachment to ground and to the grid are fulfilled
		10	Condition for attachment to ground and to the grid are fulfilled
		11	Probable attachment to mesh
		12	Attachment to mesh
IV	20 x 20	14	Probable attachment to mesh
		15	Attachment to mesh

Table IV presents the results for the protection of the building using mesh on top of the building for meshes of 5x5, 10x10, 15x15 and 20x20 m. The mesh is located on the ground plane of the building.

TABLE IV. LIGHTNING CURRENT INCEPTION ON MESH ON TOP OF THE ROOF

Class LPS	**Mesh on top of the building**		
	Mesh size[m]	***Return stroke current [kA]***	***Results***
I	5x5	3	Attachment to ground
		4	Condition for attachment to ground and to the grid are fulfilled
		4.5	Attachment to mesh
II	10x10	5	Attachment to ground
		6	Condition for attachment to ground and to the grid are fulfilled
		7	Condition for attachment to ground and to the grid are fulfilled
		8	Attachment to mesh
III	15 x 15	10	Probable attachment to mesh
		12	Probable attachment to mesh
		13	Attachment to mesh
IV	20 x 20	14	Probable attachment to mesh
		15	Attachment to mesh

The results indicate that for meshes of shorter size, i.e., 5 x 5 and 10x10, independently if the mesh is constructed by hanging wires or by a mesh on top of the structure, the recommended minimum downward lightning current incepted by the lightning protection system is higher than the recommended on the IEC standards. This probably happens because the lower the downward leader current is, the closer the downward leader has to approach to be able to incept streamer-corona on the mesh conductors. Therefore, the condition to direct strike to floor is fulfilled almost simultaneously at floor and at the mesh.

It is observed that the minimum lightning currents that can be incepted by the mesh located on top of the roof are to some extent higher (7 to 11%) than those that can be incepted using the mesh formed by wires located at certain distance from the roof. This difference is because of the effect of the grounded roof; the grounded plane of the roof does not allow an enhancement of electric field to promote upward discharges from the mesh located on top of the roof. Therefore, the downward leader needs to approach closer to the mesh on top of the building to be able to incept streamer activity from it than to the mesh formed by wires located at certain height from the building.

As the downward leader approaches closer to the mesh located on top of the building than to the mesh formed by hanging wires; the probability of high electric field on the grounded roof increases and condition (b) is fulfilled often. Therefore, for this type of protection there is higher probability that the building will be stroke directly by lightning.

IV. CONCLUSIONS

Differences on the magnitude of the minimum downward lightning current to be incepted recommended by international standards and the calculations using a lightning attachment methodology have been obtained.

Calculations indicated that a mesh formed by wires located at certain distance of the grounded structure can attach lower lightning currents than a mesh located on top of the grounded roof. Because the grounded roof hinder the enhancement of electric field of the mesh work located on top of the structure.

More investigations are required in the case of structures with roof constructed of poor conductors and non-conductors.

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