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Computation of additional charge for protection against direct lightning strike by charge transfer system in "ultra-corona" mode

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Abstract: **In this paper, computation of additional charge is made for protection against direct lightning strike, by the charge transfer system, by point electrode, in "ultra-corona" mode. The influence of the voltage increase in a very small time interval is computed and its influence is taken into consideration in the computation of the additional space charge on the object. The model of the electrical thundercloud is taken into consideration with all electrical charge in it, with its corresponding heights above ground. Plotted values are presented of different heights of the charge in the thundercloud versus the additional space charge. Plotted values are presented of different horizontal distances of the object from the place where the downward leader starts in the thundercloud, projected on the earth surface. Plotted values are presented of the height of the object versus the additional space charge.**

Key words: Lightning, leader channel, volume charge density, ultra-corona, additional space charge

I. INTRODUCTION

As it is presented in [1], the increase of the voltage in a small time interval can be able to generate enough positive ions which can move away from the electrode in that small time interval, so the maximum electric field does not exceed the corona inception field E_{ci}. In [1] is shown the dependence of the intensification coefficient from the ration h/a as h is the "height" of the object, and a is the radius of curvature of the electrode. The model for the computation of the additional positive charge is based on the computation of the increase of the voltage at the top of the object, at small time interval, taking into consideration the contribution from the positive charge, negative charge from the cloud, the positive charge of the bottom of the cloud and the negative charge of the leader channel, with all of their respective images, in the exact moment before the leader enters the "striking distance" of the object.

Interpolation is made from the values for the intensification coefficient k_e which are used to compute the minimal electrical field on ground in order to get enough positive ions for protection [1]. The critical electrical field E_{ci} is calculated according a proposed formula presented in [1]. The model for direct lightning protection is done according to [2], but modified to take into consideration the effect of the leader channel when the leader is directly over the "striking distance" d_s of the object.

II. COMPUTATION OF ADDITIONAL SPACE CHARGE

The computation is based according to the simplified model of the electrical structure of the thundercloud, shown on Fig.1.

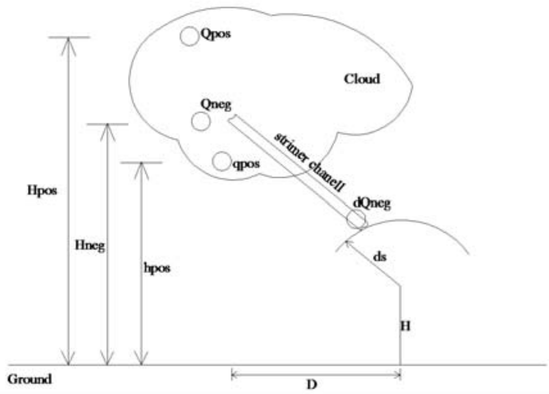

Fig. 1 Simplified model of thundercloud cell including leader channel

The engineering approach of this model is linked with a design of a simulation using the software package MATLAB, in which the simulation is designed to take as input, different parameters. As a result, we get plotted values for different input solutions. This approach is based on a few steps.

A. Step No.1 Computation of dV/dt

The computation of the increase of the voltage at the top of the object, at small time interval, is linked with [1] and with the fact that such increase, can be able to generate enough positive ions, which can move away from the electrode, placed on the top of the object, in that small time interval, so the maximum electric field does not exceed the corona inception field E_{ci}. One of the parameters that changes progressively with time is the negative charge of the leader channel. As the leader channel progresses to ground, the charge in the leader channel increases. As the charge in the leader increases, the negative charge in the cloud decreases. This means that the contribution on the computation of the increase of the voltage, at the top of the object, at small time interval is from 4 parameters: the leader channel, the leader's channel image, the negative charge in the cloud and its image.

For the leader contribution, it is approximated that the channel of the leader is a cylindrical volume in which there is a certain negative charge density. The axis along which the leader propagates is z (Fig. 2).As the leader propagates its path to ground, the voltage on the top of the object changes with time. With the approximation that the speed of propagation of the leader channel ν is constant (not taking into consideration stepped parts of the leader) it is derived that:

$$\left.\frac{dV}{dt}\right|_{z=l} = \frac{\partial V}{\partial z}\frac{\partial z}{\partial t} = \frac{\partial V}{\partial z}\cdot \nu = -E_z \cdot \nu \tag{1}$$

The leader is approximated with a cylindrical volume in which there is a charge density ρ_0 (Fig.2).

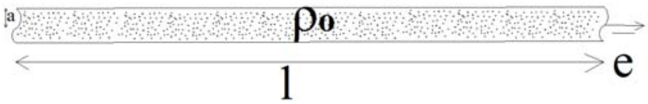

Fig. 2 Approximated leader channel with volume charge density

For computation of the electrical field along the z-axis E_z we integrate on the whole volume of the leader channel (double integral across the length of the leader channel l and across the radius of the leader channel a):

$$\vec{E}(l) = \int_0^a\int_0^l \frac{\rho_0 \cdot 2\pi \cdot rdrdz \cdot (l-z)}{4\pi\varepsilon_0 \cdot ((r^2+(l-z)^2)^{3/2}} \cdot \vec{e_z} \tag{2}$$

Solving the double integral and substituting in (1) we get the contribution of the leader channel for dV/dt as:

$$\left.\frac{dV}{dt}\right|_l = \upsilon \cdot \frac{\rho_0}{2\varepsilon_0} \cdot [l + a - \sqrt{a^2+l^2}] \tag{3}$$

Where:

υ Is the speed of the leader channel (approximated constant) [m/s]

ρ_0 Is the charge density (approximated equally distributed along the leader channel) [C/m^3]

ε_0 Is the vacuum permeability ($8.854 \cdot 10^{-12}$) [F/m]

l Is the length of the leader channel [m]

a Is the radius of the leader channel [m]

For the contribution from the image of the leader channel, we use the method of image shown on Fig. 3 and by using formula (4) from [3].

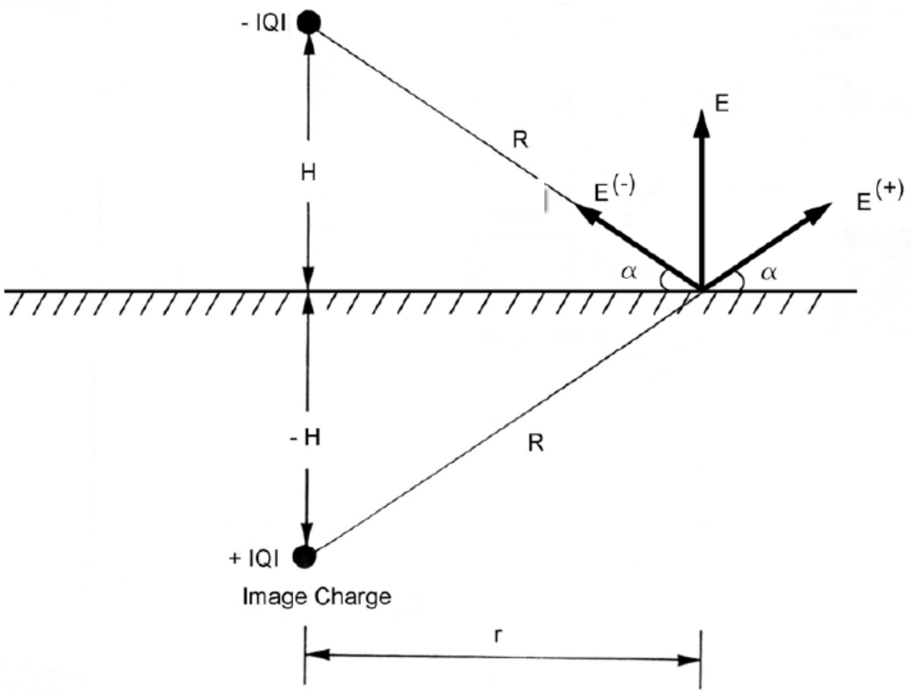

Fig. 3 Method of image for computation of electrical field from negative charge over ground

$$|E| = 2\left|E^{(-)}\cos(90^0 - \alpha)\right| = \frac{|Q|H}{2\pi\varepsilon_0 (H^2 + r^2)^{3/2}} = k\frac{\sin\alpha}{R^2} \quad (4)$$

As referring to the formula (1), the integration for the electrical field from the image of the leader channel is:

$$\vec{E}_{imagez} = \int_0^l \frac{\rho_0 \cdot dz'(z - z')}{4\pi\varepsilon_0((r^2 + (z - z')^2)^{3/2}} \quad (5)$$

By solving the integral across the length of the image of the leader channel it is derived that:

$$\frac{dV}{dt}_{image} = \upsilon \cdot \frac{\rho_0}{4\pi\varepsilon_0}\left[\frac{1}{\sqrt{(z - z_2)^2 + a^2}} - \frac{1}{\sqrt{(z - z_2)^2 + b^2}}\right] \quad (6)$$

Where:

z Is the leader length projected to image leader [m]

a Is the distance of V=0 (ground) point from image leader line [m]

z_2 Is the length of the leader [m]

b Is the distance of (D, H) point (top of the object) from image leader line [m]

For the last contribution, from the negative charge in the cloud and its image, it is derived that:

$$\frac{dV}{dt} = \overset{-}{+}\frac{\rho_0 \pi a^2 \upsilon}{4\pi\varepsilon_0 r_{\underset{-}{+}}} \quad (7)$$

Where:

r Is the distance from negative charge in the thundercloud and its image to point (D, H) (top of object) [m]

Finalizing step No.1 by sum of the formulas (3), (6) and (7) the result for dV/dt is obtained as:

$$\frac{dV}{dt}_{all} = \upsilon \cdot \frac{\rho_0}{2\varepsilon_0} \cdot [l + a - \sqrt{a^2 + l^2}] +$$
$$\upsilon \cdot \frac{\rho_0}{4\pi\varepsilon_0}\left[\frac{1}{\sqrt{(z - z_2)^2 + a^2}} - \frac{1}{\sqrt{(z - z_2)^2 + b^2}}\right] + (\overset{-}{+}\frac{\rho_0 \pi a^2 \upsilon}{4\pi\varepsilon_0 r_{\underset{-}{+}}}) \quad (8)$$

B. Step No. 2 Computation of critical field intensification E_{ci}

The condition for finding E_{ci} is used from [1], by using the fact that to maintain ultra-corona on a spherical electrode, the rate of voltage rise should satisfy:

$$\frac{dV}{dt} \leq 2\mu E_{ci}^{\ 2} \quad (9)$$

C. Step No.3 Computation of intensification coefficient k_e

Using [1], approximation is made by using a radius of curvature of 1 meter, as a constant value for the used electrode and the intensification coefficient k_e values are interpolated. Every value of the intensification coefficient k_e corresponds to a value of the height H of the object. As the intensification coefficient k_e is limited in the interval of [10, 90], the values of the height H of the object is also limited to the interval of [10, 200].

D. Step No.4 Computation of the minimal ground electrical field $E_{0\min}$

Based on the procedure proposed in [2], the formulas for the computation of the ground electrical field are based on the assumption that the negative charge $dQneg$, going from the thundercloud into the leader channel is placed on the tip of the leader channel (See Fig.1). The moment that is a “point of interest”, is the moment when the leader channel is at the point before entering the “striking distance” d_s of the object. The intention is to calculate the additional charge needed exactly in that time, in order to establish an ultra-corona condition (streamer free) on the top of the electrode. At that moment, by already computed E_{ci}, and by already computed set of values for k_e and the height of the object H, the intention is to get the result for the minimal ground electrical field in order to have enough positive ions at the top of the object in ultra-corona mode.

As previously mentioned, the negative charge in the leader channel can be computed by:

$$dQneg = \rho_0 \cdot a^2 \cdot \pi \cdot l \quad (10)$$

Where:

l Is the length of the leader channel [m]

By using Fig.1 and Fig.3, the minimal ground electrical field is derived as:

$$E_{0\min} = -\frac{2\cdot Q_{pos}\cdot H_{pos}}{4\pi\varepsilon_0\cdot(H_{pos}{}^2+D^2)^{3/2}} + \frac{2\cdot Q'_{neg}\cdot H_{neg}}{4\pi\varepsilon_0\cdot(H_{neg}{}^2+D^2)^{3/2}}$$
$$-\frac{2\cdot q_{pos}\cdot h_{pos}}{4\pi\varepsilon_0\cdot(h_{pos}{}^2+D^2)^{3/2}} - \frac{2\cdot q_{sc}\cdot h_{sc}}{4\pi\varepsilon_0\cdot(h_{sc}{}^2+D^2)^{3/2}} +$$
$$+\frac{2\cdot dQ_{neg}\cdot H_T}{4\pi\varepsilon_0\cdot(H_T{}^2+D^2)^{3/2}} \qquad (11)$$

The negative charge Q'_{neg} is the charge that is left in the thundercloud after the leader channel reached the striking distance of the object. That is why $Q'_{neg} = Q_{neg} - dQ_{neg}$. The result for the additional positive charge q_{sc} on the top of the object in ultra-corona mode is calculated per formula (11).

III. RESULTS FROM THE COMPUTATION

Based on the abovementioned formulas, simulation is made using the software package MATLAB. The input parameters for the simulation are:

- Q_{pos}, Q_{neg} and q_{pos} charge in the thundercloud,
- H_{pos}, H_{neg} and h_{pos} heights above ground of the charge located in the thundercloud,
- Horizontal distance D between the point of formation of the negative leader channel in the cloud, (its projection to ground) and the object,
- Height of the object H (with limited values),
- Volume charge density ρ_0 in the leader channel,
- Speed of propagation υ of the leader channel
- Coefficient of ion mobility μ

Respecting these input parameters, the results of the simulation are based on the input values taken from [3]. The model of the vertical triple charge, representing the idealized gross charge structure of thundercloud, is used. The volume charge density is also adopted by [3], representing the average charge density and by assuming that the field is constant. Assumption is also made that this average charge density is constant during the whole length of the leader channel. The results are presented as follows:

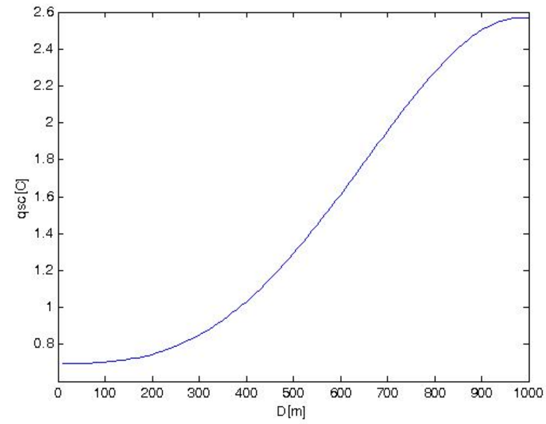

Fig.4. Quantity of additional charge q_{sc} versus distance D (for a height of the object H=100 m)

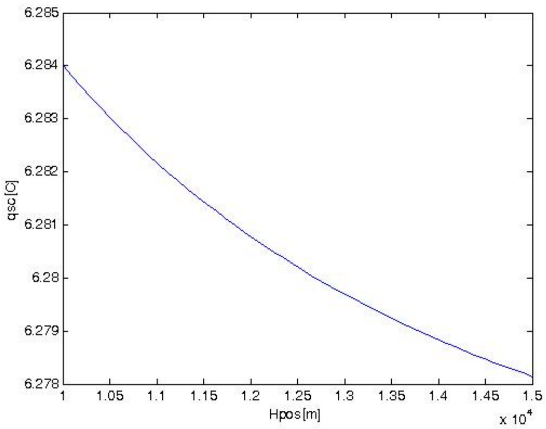

Fig.5. Quantity of additional charge q_{sc} versus height H_{pos} (for a height of the object H=60 m and distance D=100m)

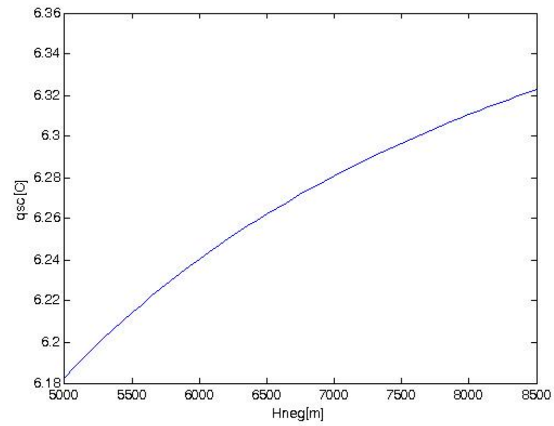

Fig.6. Quantity of additional charge q_{sc} versus height H_{neg} (for a height of the object H=60 m and distance D=100m)

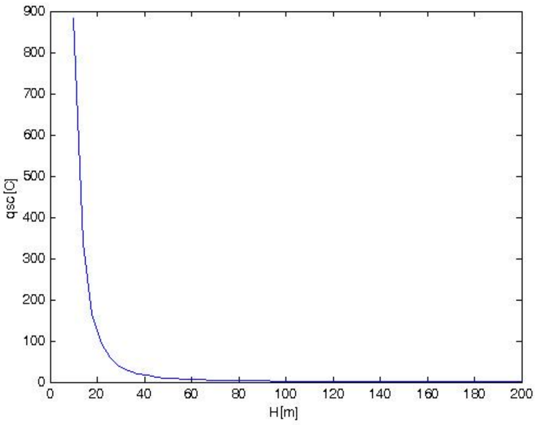

Fig.7. Quantity of additional charge q_{sc} versus height of the object H (for distance D=100m and radius of curvature=1m)

IV CONCLUSIONS

As shown on Fig.4, by increasing of the distance from the projection to ground of the point where the leader has started in the thundercloud, to the object, more additional charge is needed in ultra-corona mode (streamer free) for protection from direct lightning. This is because the length of the leader channel is longer compared to the situation when the start of the leader channel is just above the protected object.

As the height of the object increases, the required additional charge, on the top of the object, needed for protection decreases (Fig. 7). The smallest quantity of charge needed for protection is when the height of the object is above 30 meters (for radius of curvature of 1 meter taken as a constant value of entire range of values). The simulation results show that the charge transfer system is not practical for protection of objects that do not have sufficient height, for placement of the electrode, above 30 meters (substations etc). The needed additional space charge is less for heights above 30 meters, so the usage is preferable for objects that do have "natural" constructive heights like telecommunication towers, chimneys of power plants etc.

The change of the height above earth, in the simulation, of the located positive and negative charge in the thundercloud, does not have a significant effect in the computed quantity of the additional charge needed for protection (See Fig. 5 and 6). The simulated values for the heights above ground, of the positive charge in the thundercloud, from 10000 meters to 15000 meters, showed that it does not have significant influence on the quantity of the additional space charge needed for protection (Fig. 5). The same is for the change of the height above ground, in the simulation, of the negative charge in the thundercloud, as the simulated values are in the range of 5000 meters to 8500 meters and they do not have significant influence on the quantity of the additional space charge needed for protection (Fig. 6).

The computation also has shown that the value of the increase of the voltage at the top of the object, at small time interval is 99% contributed by the leader channel itself. The other part (the image of the leader, the negative charge and its image) has only 1% contribution to this value.

The simulation gives the possibility for input values for positive and negative charge of the thundercloud, respectively their heights above ground, distance between the point of formation of the leader channel in the cloud, (its projection to ground) and the object, the height of the object (with limited values in the simulation), volume charge density in the leader channel, speed of propagation of the leader, coefficient of ion mobility. The input data in the simulation, for the positive and negative charge in the thundercloud, can vary from region to region. The data used for the presented results, in this paper, were the values taken from [3]. Any new obtained data concerning the previously mentioned parameters can be used as an input in the simulation.

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