CALCULATION OF THE PROBABILITY FOR THE FLASHOVER OF THE INSULATOR STRING DUE TO THE LIGHTNING STROKES ON THE PHASE CONDUCTOR. PART I. PRESENTATION

Virgil CRUCEANU[1], Dorin CRISTESCU[2]

În normativul național [1] privind protecția instalațiilor electroenergetice împotriva supratensiunilor, se defineşte zona de protecție a unui paratrăsnet (fie el vertical sau orizontal) ca fiind spațiul cuprins din jurul paratrăsnetului în care un obiect este protejat cu un factor de risc de 10^{-3} *împotriva loviturilor directe de trăsnet datorate orientării trăsnetului spre paratrăsnet.*

Spre deosebire de standardele internaționale [2], [3], respectiv ghidul [4], în acest normativ nu se specifică o metodă de calcul al factorului de risc privind loviturile directe de trăsnet pe conductoarele active, lovituri datorate defectului de ecran.

Pentru identificarea unei soluții optime de protecție a LEA împotriva supratensiunilor de trăsnet, devine important alegerea metodei de modelare şi analiză a descărcărilor atmosferice.

The protection zone of a lightning rod (vertical or horizontal) is defined in the Romanian normative [1], related to the protection of electro energetic equipment against over voltage, to be the space around the lightning rod inside of which an object is protected up to a risk factor of 10^{-3} *against the lightning strokes due to the downward leader orientation towards the rod.*

In contrast with the international standards [2], [3], and the guide book [4] respectively, there is no method inside of this normative, to calculate the risk factor for lightning strokes on phase conductor.

Therefore, to indicate an optimal solution for protecting the Over Head Lines (OHL) against over voltage due to lightning, it becomes important and necessary to choose a modeling and analyzing method for atmospheric discharges.

Keywords: OHL, flashover, leader, lightning protection, lightning model, shielding failure

[1] Eng., Fichtner Engineering SA, Bucharest, România, e-mail: cruceanu_virgil@yahoo.com
[2] Prof., Faculty of Electrical Power Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: dcris@el.poweng.pub.ro

1. Introduction

Starting from experimental investigations, the now-a-day studies succeeded to split into groups the methods for calculating, using the existing models, the shielding failure created by the ground wires:

- models based on the orientation distance such as: the electro-geometric model (EGM), the model of the fictive sphere etc.;
- models based on the orientation distance and the intensification factor determined by the height of the structures from the ground, such as: the model proposed by EDF and UPB, the developed electro-geometric model (DEGM), the generalized model of triggered leader (GTLM) etc.;
- models based on the kinematics of the two leaders such as: leader progression model (LPM) etc.

This paper is the result of the researches in [8]; the authors propose a new method to calculate the probability of shielding failure appearance. Shielding failure represents a gap into the protection system of the ground wires, gap given by the direct lightning strokes on the phase conductors.

This importance of building such a method is amplified due to the fact that Romanian normative [1] for protection of electro energetic equipment against over voltage, are imposing only a specific protection degree, without really indicating a viable way to complete such calculations.

The authors consider this method as a mathematical interpretation of the leader progression model (LPM) for an Over Head Line (OHL) with one or two ground wires.

2. Leader Progression Model (LPM)

The models based on the kinematics of the two leaders are taking into account the gradual propagations in space and time of the downward leader and the upward one. The idea is to calculate the direction of the maximal electrical field in front of the streamers' zone, after each several meters propagation step of the two leaders.

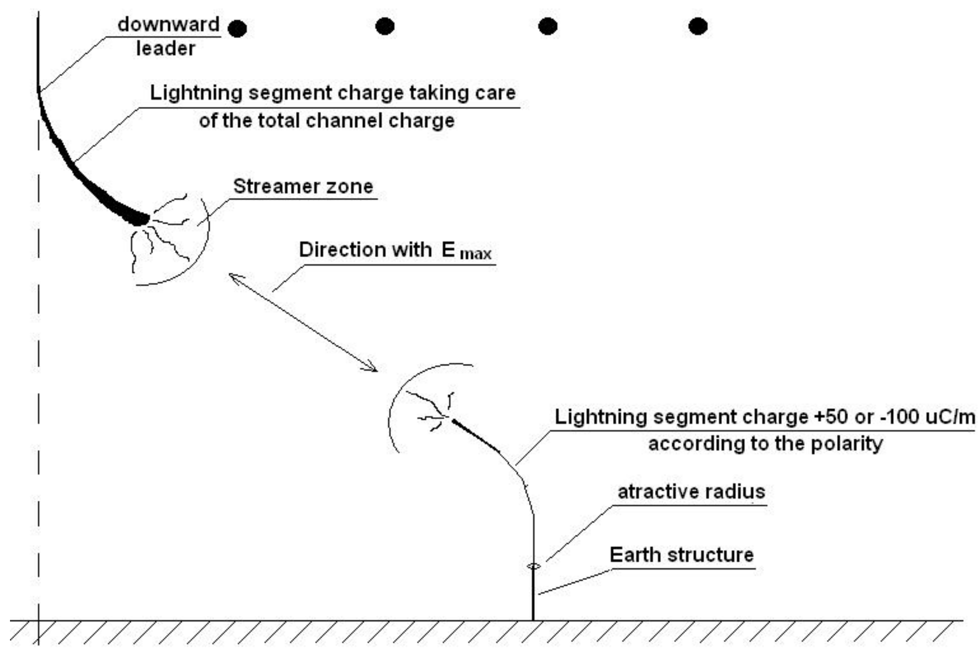

Fig. 1. The step by step simulation of the two leaders, conform MAL [5]

Dellera [5] schematically presented in Fig. 1 the step by step simulation of the two leaders. The cloud with a 10 km in diameter is simulated using four charge rings with equally spaced with uniform charge density over the cloud area. The charges used to simulate the ground structure and the profiles of the terrain are: linear charge, spherical charge, conductor charge. The critical radius was defined as the minimum radius at which the starting upward leader appears, without the preliminary starting of the corona discharge.

It was observed that:

- the expansion of the streamers' zone appears in the area where the electrical field at the ground is greater to equal to 3 kV/m;
- the initiation of the upward leader appears when the electrical field reaches the critical value of 310.6 V/m calculated by Carrara at the fictive end of the corona critical radius' extremity.

The choice of "equivalent charges" for modeling the structure on the ground (radius and value) is very important for the LPM. The points on the structure where the upward leader is initiating can be determined using these radii and the height dependency of the "critical radius". As a matter-of-fact, the downward leader that gets inside of a cylinder of radius *LD* will hit the structure situated on the ground.

A numerical analysis of the curves obtained using MAL leaded to the conclusion that *LD* (lateral distance) and *PDg* (protective ground distance) are functions of the structure's height *h* and of the amplitude *I* of the lightning's current:

$$\begin{cases} LD = f(h,I) \\ PDg = g(h,I) \end{cases} \quad (1)$$

For simplification, some authors [6], [7] proposed for engineering calculations the following relations:

$$\begin{cases} LD = A(h)\cdot I + B(h) \\ Pdg = C(h)\cdot I + D(h) \end{cases} \quad (2)$$

where: $$\begin{cases} A(h) = \alpha_1 \cdot h + \beta_1 \\ B(h) = \gamma_1 \cdot h + \tau_1 \end{cases} \quad (3)$$

and $$\begin{cases} C(h) = \alpha_2 \cdot h + \beta_2 \\ D(h) = \gamma_2 \cdot h + \tau_2 \end{cases} \quad (4)$$

Table 1

Coefficients for the lateral distance *LD* [7]

	α_1	β_1	γ_1	τ_1
A	0,011052	0,08566		
B			0,04244	10,370175

Table 2

Coefficients for the protective ground distance *PDg* [7]

	α_2	β_2	γ_2	τ_2
C	0,1054625	0,147375		
D			0,3667325	6,81675

3. The proposed method for LPM

The first step that one will consider is to determine the $f_{cp}(x)$ function. From a geometrical point of view, the graph of this function has the propriety that it is a place from where the lightnings are oriented towards the ground wire with the same probability that they are oriented towards the ground.

To exemplify, let's consider a Guyed tower type having the origin *O* in the middle of its base. The prints for each of the phase and ground wires are represented by the points $A(x_A,y_A)$ and $B(x_B,y_B)$, respectively.

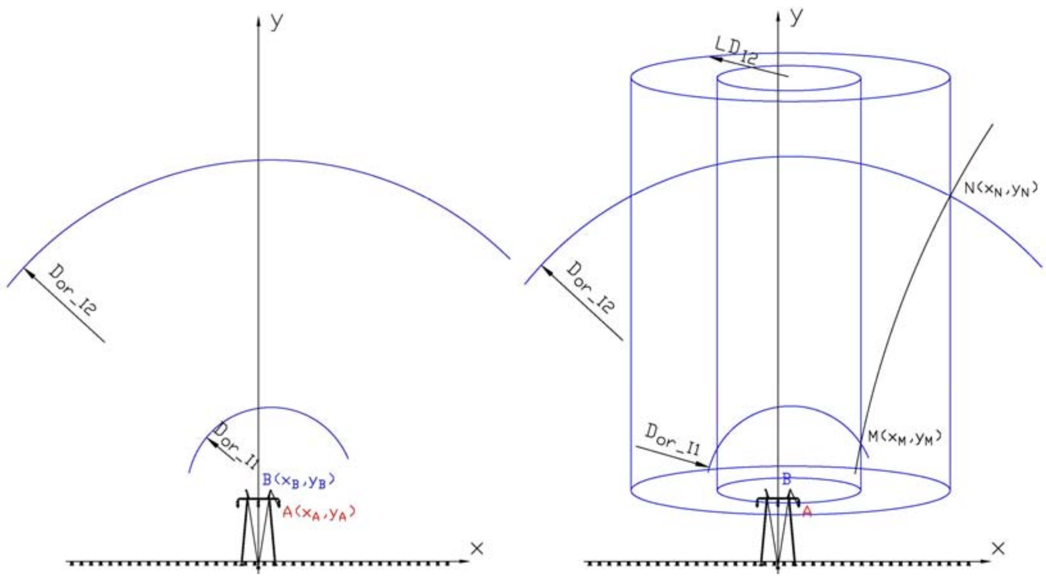

Fig. 2. The striking distances D_{or_I1}, D_{or_I2} and the lateral distances LD_{I1}, LD_{I2}

Consider also two lightning falling to the right peak of Guyed tower type. Two arcs with center in $B(x_B,y_B)$ and of radii $D_{or\_I_1}$ and $D_{or\_I_2}$, each one for I_1 and I_2 (the amplitudes of the first and second lightning's currents respectively) have been drawn.

$$D_{or\_I} = \alpha \cdot I^{\beta} \tag{5}$$

where:

D_{or_I} – the radius of orientation [m]

I – the amplitude of the electrical intensity field [kA]

α, β – constants (α=9,4 β=2/3);

or,

$$D_{or\_I} = I^{a} \cdot 0{,}8 \cdot h^{0{,}6} \tag{6}$$

where:

h [m] – the height of the structure

$a = 0{,}7 \cdot h^{0{,}002}$.

According to LPM, the laterals distances LD_{I_1} and LD_{I_2} are corresponding to the amplitudes of the lightning's currents I_1 and I_2.

If we denote by M the intersection point between the arc of radius $D_{or\_I_1}$ and the lateral distance LD_{I_1}, and N the intersection point between the arc of radius $D_{or\_I_2}$ and the lateral distance LD_{I_2}, then we can write:

$$\begin{cases} x_M = x_B + LD \\ y_M = y_B + \sqrt{D_{or}^2 - (x_M - x_B)^2} \end{cases} \tag{7}$$

where:

$$\begin{cases} LD = (\alpha_1 \cdot y_B + \beta_1) \cdot I + (\gamma_1 \cdot y_B + \tau_1) \\ D_{or} = \alpha \cdot I^{\beta} \end{cases} \tag{8}$$

From (7) and (8) we obtain:

$$\left\{ I = \frac{(x_M - x_B) - (\gamma_1 \cdot y_B + \tau_1)}{\alpha_1 \cdot y_B + \beta_1} \right. \tag{9}$$

From (7), (8) and (8) we obtain:

$$y_M = y_B + \sqrt{\left\{ \alpha \cdot \left[\frac{(x_M - x_B) - (\gamma_1 \cdot y_B + \tau_1)}{\alpha_1 \cdot y_B + \beta_1} \right]^{\beta} \right\}^2 - (x_M - x_B)^2} \tag{10}$$

In other words, the function $f_{cp}(x)$ (for which the graph is given by the intersection of the arcs with D_{or} radius and cylinders with LD radius, see Fig. 3) has the following expression:

$$f_{cp}(x) = y_B + \sqrt{\alpha^2 \cdot \left[\frac{(x - x_B) - (\gamma_1 \cdot y_B + \tau_1)}{\alpha_1 \cdot y_B + \beta_1} \right]^{2\beta} - (x - x_B)^2} \tag{11}$$

where:

x_B [m] – horizontal coordinate of B (the position of the ground wire)

y_B [m] – vertical coordinate of B

α_1, β_1, γ_1 and τ_1 – determined coefficients in Table 1 for *LD;*

α, β – constants (α =9,4 β=2/3);

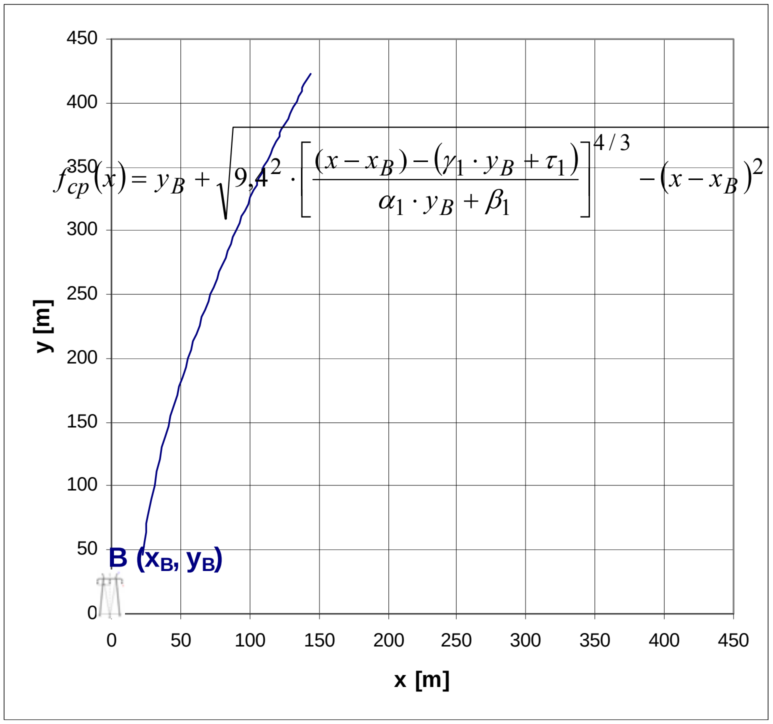

Fig. 3. The orientation zone of the lightning falling on *B* (the print of the ground wire)

To simplify the graphic representation of the zone where the lightnings are falling in $B(x_B,y_B)$, we have not drawn anymore the cylinders for which the radius (given by the lateral distance) depends on the amplitude of the lightning's current that falls on the tower's peak. From a geometrical point of view, the lightning starting on the point at the top of the graph for $f_{cp}(x)$ will hit the ground wire.

Let's denote by $I_{\min}$, I_{cont} and $I_{\max}$ the values of the amplitudes extracted from a database (see the Lightning Localization System) for a given period of time, respectively from the zone where our guyed tower type is standing. The following are corresponding to these values:

- the arc with the center in the print of the ground wire and of radius $D_{or\_cp\_I_{\min}}$, corresponding to the geometrical space of the points from where a lightning with the amplitude $I_{\min}$ of the current strokes on the ground wire;
- the arc with the center in the print of the ground wire and of radius $D_{or\_cp\_I_{cont}}$, corresponding to the geometrical space of the points from where a lightning with the amplitude I_{cont} of the

current strokes the ground wire and produces, at limit, the inverse flashover of the insulator string;

- the arc with the center in the print of the ground wire and of radius $D_{or\_cp\_I_{max}}$, corresponding to the geometrical space of the points from where a lightning with the amplitude I_{max} of the current strokes the ground wire.

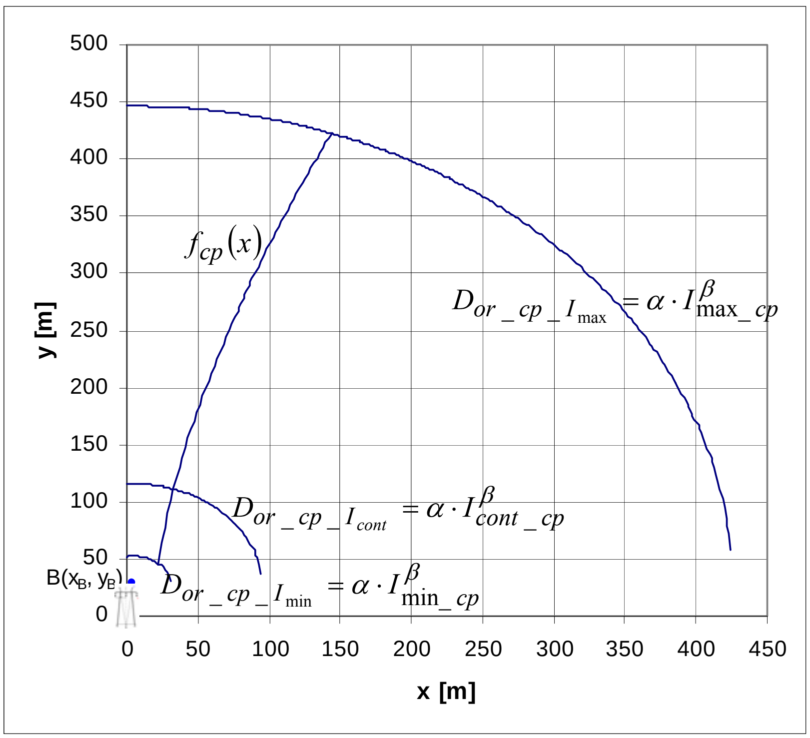

Fig. 4. Calculation of the shielding failure: 1st step. Draw the function $f_{cp}(x)$ and the arcs with afferent radii $D_{or\_cp\_I_{min}}$, $D_{or\_cp\_I_{cont}}$, $D_{or\_cp\_I_{max}}$

$$\begin{cases} D_{or\_cp\_I_{min}} = \alpha \cdot I^{\beta}_{min\_cp} \\ D_{or\_cp\_I_{cont}} = \alpha \cdot I^{\beta}_{cont\_cp} \\ D_{or\_cp\_I_{max}} = \alpha \cdot I^{\beta}_{max\_cp} \end{cases} \tag{12}$$

The afferent function to the orientation zone of the lightning falling in *A* (the print of the active conductor) can be similarly determined:

$$f_{ca}(x) = y_A + \sqrt{\alpha^2 \cdot \left[\frac{(x - x_A) - (\gamma_1 \cdot y_A + \tau_1)}{\alpha_1 \cdot y_A + \beta_1}\right]^{2\beta} - (x - x_A)^2} \qquad (13)$$

The distances of orientation for the active conductor become:

$$\begin{cases} D_{or\_ca\_I_{\min}} = \alpha \cdot I^{\beta}_{\min\_ca} \\ D_{or\_ca\_I_{cont}} = \alpha \cdot I^{\beta}_{cont\_ca} \\ D_{or\_ca\_I_{\max}} = \alpha \cdot I^{\beta}_{\max\_ca} \end{cases} \qquad (14)$$

Similar as in the first step, once can now trace in the second step the function $f_{ca}(x)$ and the arcs with the center in the print of the active conductor and of radii $D_{or\_ca\_I_{\min}}$, $D_{or\_ca\_I_{cont}}$, and $D_{or\_ca\_I_{\max}}$ respectively.

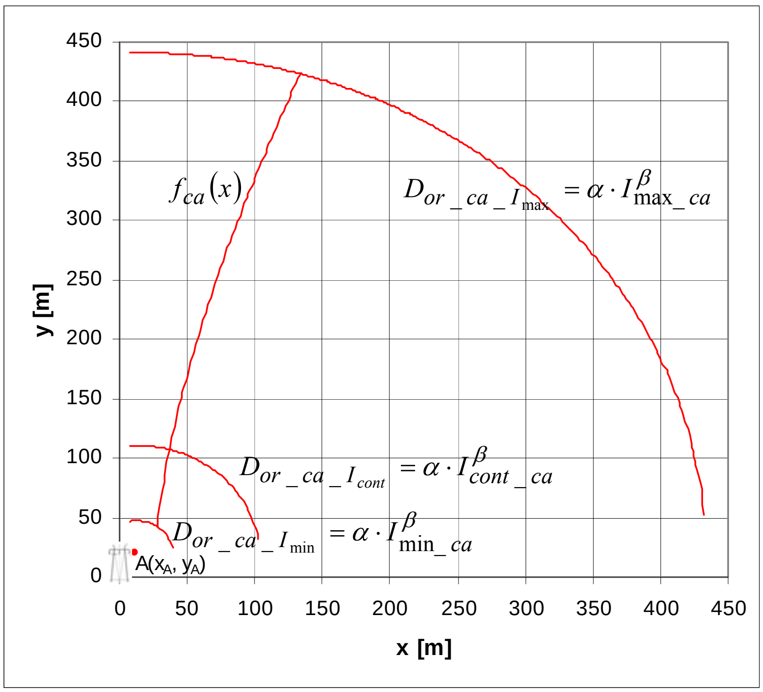

Fig. 5. Calculation of the shielding failure: 2nd step. Draw the function $f_{ca}(x)$ and the arcs with afferent radii $D_{or\_ca\_I_{\min}}$, $D_{or\_ca\_I_{cont}}$, $D_{or\_ca\_I_{\max}}$

One will define the log-normal repartition function of the lightning currents in the third step and will calculate the probability for lightning current appearance on the phase conductor in A, lightning current that will produce the flashover of the insulating string.

The amplitudes of the lightning's currents are "listening" to a log-normal repartition function of the form:

$$p(\ln I) = \frac{1}{\sigma I \sqrt{2\pi}} \cdot e^{-\frac{\left(\ln I - \ln \bar{I}_0\right)^2}{2\sigma^2}} \qquad (15)$$

where:

$\sigma \approx 0{,}3$ – the standard deviation (collected from database);

$\bar{I}_0 \approx 31$ kA – average value of the lightning's current (collected from database);

$p(\ln I)$ – the log-normal repartition function (I instead of ln$I$ on the x-axis),

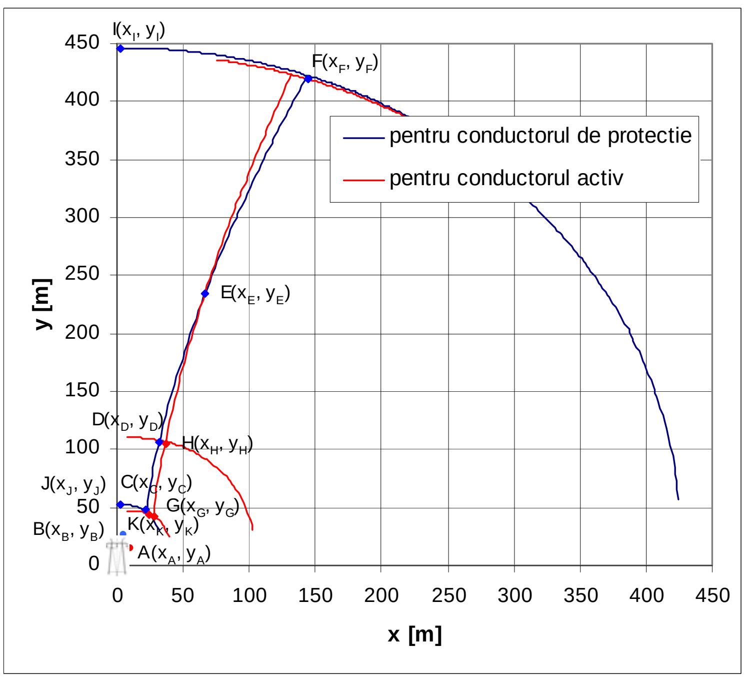

Fig. 6. Calculation of the shielding failure: 3[st] step. Calculation of the probability for lightning current I appearance on the phase conductor in A, with $I > I_{flashover}$

Now, we can write the probability for lightning current appearance on the phase conductor in A, lightning current that will produce the flashover of the insulating string.

$$PC_{punct\_A} = \frac{\iint\limits_{DEH} p_{(\ln I)} \cdot dx \cdot dy}{\iint\limits_{JCKGHEFIJ} p_{(\ln I)} \cdot dx \cdot dy} \qquad (16)$$

In the fourth step, we can calculate the probability for flashover of insulator string $P_{flashover}$:

$$P_{conturnare} = 2 \cdot D_{sol} \cdot L \cdot (PC_{punct\_A} \cdot k_{egalizare}) \qquad (17)$$

were:

D_{sol} - ground flash density;
L – the length of the Over Head Line;
$k_{egalizare}$ – the constant which takes into consideration the coefficient of equalization between ground wire and phase conductor.

4. Conclusions

The authors build a method to calculate the probability for the flashover of the insulator string of an Over Head Line, due to the direct lightning stroke on the phase conductor. Looking at the method of calculating the orientation distances $D_{or\_cp\_Icont}$ and $D_{or\_ca\_Icont}$ (distances that brings the flashover for the insulator string), once can observe that the proposed model takes into account the following:

- the geometry of the towers;
- the impedances for the towers and conductors;
- the earth resistance for each towers;
- the chosen insulating level (electrical dimensioning of the insulator string);

but also, the following:

- the lightning development using the LPM.
- the min. and max. amplitudes of the lightning's currents falling on Over Head Lines;
- the log-normal repartition function of the amplitudes of the lightning's currents

The coefficients found in our relations, the distribution function for the amplitudes of the lightning's currents and the steps used in our method of calculus, can be improved if the data collected from the Lightning Location System are correlated with the events from power plants.

Building the relations and finding a numerical solution to solve them is part of [8] and will be the subject of the next article named "Calculation of the probability for the flashover of the insulator string due to the direct lightning on the phase conductor. Part II. Mathematical solution and numerical approach".

In the part III, the authors will check the validation of the proposed method. For that, the results of the proposed method will be compared with the ones given by FLASH 2.0 program [3].

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