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Critical feedback on the methods of determining the impact of lightning on power system objects

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***Abstract* -- The methods still use in Romania to assess the protection effectiveness against lightning, derives from physical modeling, on reduced-scale models, of protected facilities and means of protection such as lightning rods and protection conductors. Therefore an analysis of the new methods assessing this problem was necessary. Electrogeometric model (MEG), the developed electrogeometric model (MEGD) or generalized model of triggered leader (MGDL) are analyzed and compared in this article.**

***Index Terms* -- lighting; lighting model; lighting protection;**

I. Introduction

THE purpose of this research is to present a methodology for engineers to estimate how the lightning strakes the electrical lines and the procedures for designing the canopy layout of electrical lines pillars, regarding the positioning of protective conductors in order to reduce the numbers of lightning in phase conductor, causing the insulation brake down [1].

The analysis is based on considering the physical processes undertaken during the final stages of advancement of the downward leader, usually negative, towards land or structures such as the electrical lines. This process is highly complex and the role of metallic structure have been the subject of numerous studies and research conducted during latest 60 years, by Schonland, Gold, Berger and Wagner [2], or later Delera and Garbagnati [3] Erikson [4] and Rizk [5].

The methods still use in Romania to assess the protection effectiveness against lightning, derives from physical modeling, on reduced-scale models, of protected facilities and means of protection such as lightning rods and protection conductors.

In recent year's new models ware propose such as the MEG electrogeometric model, (Gold, Whitehead) the developed electrogeometric model MEGD (Eriksson) or generalized model of triggered leader MGDL (Dellera).

After 1990, the concept of upward leader propagation towards the descendant leader is introduced by Dellera and Garbagnati, using the latest research and models of long discharges strikes and the laboratory lightning test results (EDF-research UPB). In principle, a structure to be strike by lighting requires the meeting of the two leaders. New concepts are use, as striking distance or attraction radius (space volume above the structure in which the interception is happening).

However there isn't unanimous consensus between worldwide researchers regarding most suitable approach, in particular due to the randomness of lightning phenomenon and the divergence of views on applicable probabilistic distributions; the emergence of new methods in lightning location (LLS) has not simplified the problem due to strike location uncertainty and appearance of new probabilistic elements.

II. Direct lightning impact, models.

The mechanisms of lightning impact have several approaches. The "history" or electrogeometric model (Gold, Wbitchcad) is based on the notion of "striking distance" - distance between the top of the structure and the downward leader front when the dielectric possibilities of the air interval are overcome due to electric field is one of them.

Improved electrogeometric model developed by Eriksoncare (1987) take in to consideration the electrical charge of downward leader when calculating electric field (MEGD).

Oder approach proposed by Dellera and Garbagnati in 1990 is the generalized trigger leader model (MGDL).

In all these models is not taken into account the leaders propagations downward and upward and consequently they don't determine the actual pathways after upward leader initiation which causes some uncertainties in finding the actual impact point on the structure in question. These elements are more important when electric field configuration is more complicated or other structures are nearby and can influence the phenomena. To overcome these difficulties is necessary to dynamically simulate the leader propagation, based on a combined calculation of the electric field in order to draw the most appropriate leader development.

This was done with the model of "the leader advancement" (MAL), since 1990.

Knowing that the geometry of high voltage lines is relatively well determined, the statistics on lightning impact is most reliable. Therefore the validity of these models can be checked and confirmed by these data.

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Also is important to emphasized that the relevant results to the transport lines are always evaluated taking into account the lower currents, while for assessing the risk of non lightning interception on a certain protected structure, is very important to consider in particular the lowest current.

In what follows in this chapter elements for evaluation of models in a parametric study in comparison with actual behavior for the first 3 approaches will be presented.

A. Improved electrogeometric model (MEGD)

Compared with historical model in which distance of discharge is a current amplitude function, Erikson [6], [7] proposed in 1987 a rational basis for considering the structure height.

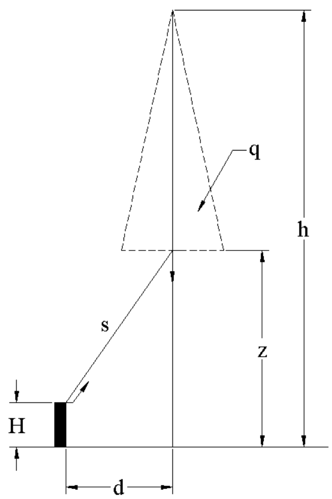

Fig. 1. Downward leader approach to the structure.

Erikson "Fig. 1" introduces a number of assumptions in order to obtain a solvable model. First it is assumed that the structure in question is approximately vertical with a cylindrical geometry, the main branch of the downward leader approaches can be estimated with a linear route and criteria to initiate upward leader from a particular structure is the achievement of critical electric field intensity (310.6 V/m) at the end of the fictitious critical corona radius.

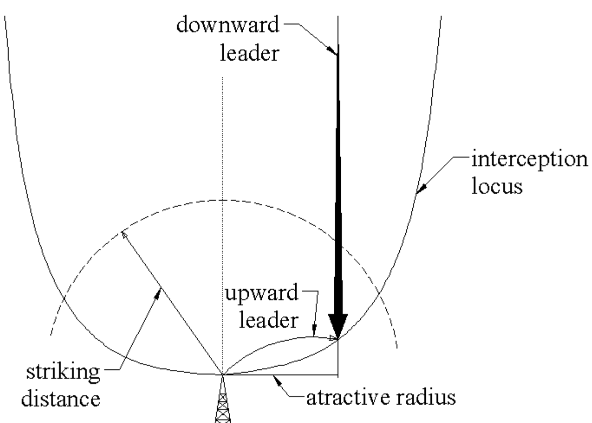

Fig. 2. Interception of the downward leader by upward connecting leader at the limit of the attraction radius of the structure. (MAL)

The strike will fall on the structure only if the downward lieder will intercept the upward leader "fig. 2".

With the previous assumption, the lightning impact on the structure is possible only when the downward leader tip reaches the volume on top of the structure defined by the attractive radius "R_a".

Analyzing the approximation with one of regression methods is possible to determine for the attraction radius, next equation:

$$R_a = i^a \cdot 0.84 \cdot h^{0.6} \quad [kA,\ m] \tag{1}$$

where $a = 0.7 \cdot h^{0.02}$.

Comparing with the field observations may be proposed a simplified formula.

$$R_a = 14 \cdot h^{0.6} \tag{2}$$

with a reference to a current of 35 kA valid for heights between 10 to 100 m.

In Fig. 3 (*a*) and (*b*) is shown the comparison between the data calculated with the simplified equation (2) and experimental data from field observations on structures and transmission lines.

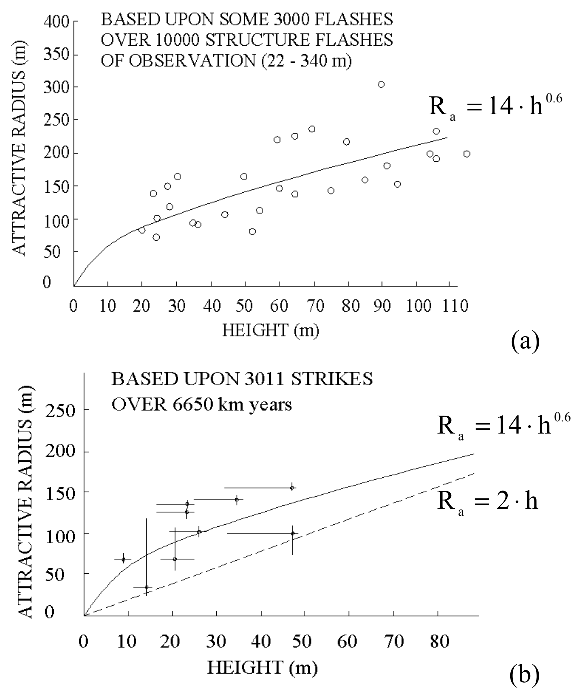

Fig. 3. Comparison between the MEGD model data and field observations results. (a) Vertical structures - tall, (b) electrical lines.

B. Generalized producing leader model (MGDL).

In the lightning impact model – MGDL – is also taken in to account the positive leader initiation from the ground objects under the influence of the downward negative leader or the propagation phenomenon of the two channels.

To determine the trajectory of positive leader requires few assumptions, including the relative speed advancement of the leaders is considered equal to unity, and when the voltage gradient between the two leaders exceed 500 kV/m it will produce the "final jump" [8].

In literature are possible to find variations of R_a with the height of the object at a given current.

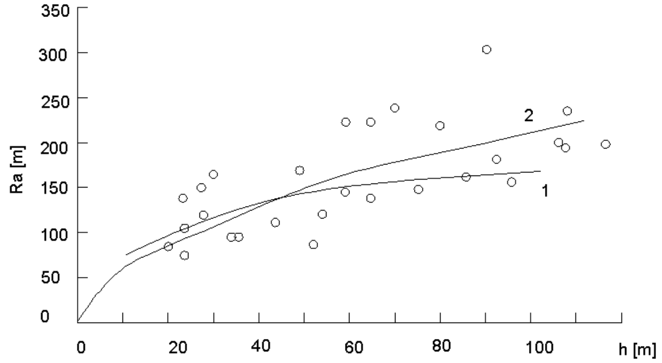

Fig. 4. Evolution of overall attractive radius R_a in relation with structure height h and data from direct observation of the electrical lines. Where 1 - the generalized producing leader model (MGDL) and 2 – developed electrogeometric model (MEGD).

For horizontal protective conductor, is used the concept of lateral attraction distance (D_a) for different currents in relation with the protector height.

Other important concept according to [8] is the overall lateral attractive distance D_{a_ac}, which can be determined by a numerical integration based on the probabilistic distribution like in equation (3).

$$D_{a\_ac}(h) = 1.13 \cdot D_a(31 \cdot h) \qquad (3)$$

Lateral attraction distance (D_a) and overall lateral attractive distance D_{a_ac}, compared with advancement of the 2 leaders study and data obtained from direct observation is presented in "fig. 5".

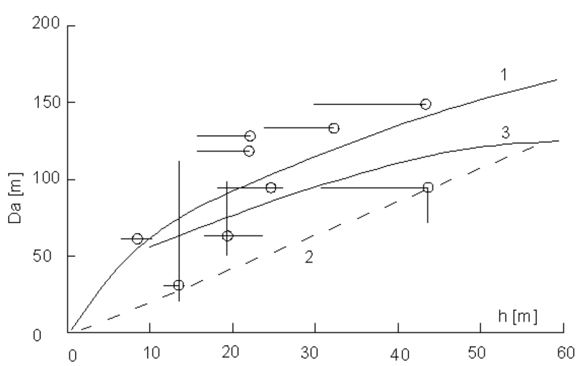

Fig. 5. Dependence with the height of the lateral attraction distance D_a and overall lateral distance D_{a_ac}. 1 - the attraction radius for vertical protector, 2 - D_{a_ac} 2 h according to IEEE, 3 - Generalized leader advancement model MGDL.

In a more exact analysis of the incidence of lightning in electrical lines, it should be useful a review of all lightning categories, the electric field intensification due to soil downward leader is particularly important. The cloud electrical charge has no significant contribution in downward leader advancing channel.

Obviously a very precise calculation should take into account the presence of the two groups of electrical charge in the cloud, presumably with a diameter of 10 km and height limit of 2 km.

Incidents statistics can be mystify by the presence of upward lightnings. Pierce [9] and McCann [10] have examined the occurrence probabilities of upward lightning in relation with the height of the object in question. These results are shown in "fig. 6".

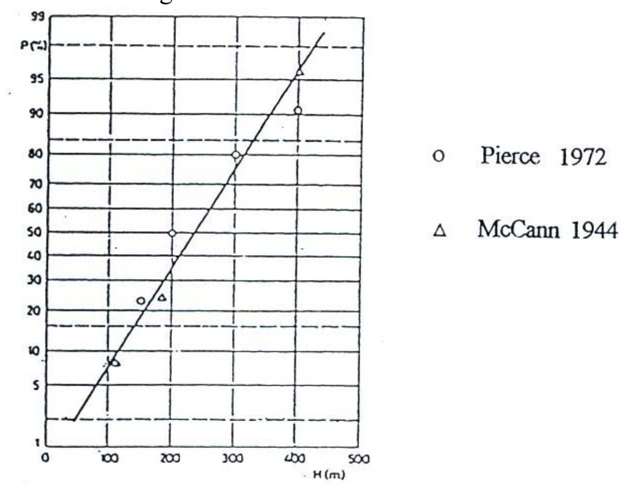

Fig. 7. The occurrence probability of upward lightning.

III. Lieder progression model (MAL)

This approach is one of the most recent methods of research of impact point.

In order to obtain usable results in the analysis of the lightning impact point it was necessary first to experiment the conditions for upward leader initiation.

Among the first works in the area have been notified in the joint research UPB-EDF, when long air gaps were stressed with positive slow front voltage pulses, which can be assimilated with electrical field evolution under downward leader stresses [11]. The concept of critical corona radius for ground electrode analyzed before was introduced later by Carara [12].

The most detailed simulation of the impact mechanisms, initiated by Dellera is a dynamic model that takes into account the leader advances in time and space. The method simulates the structure – space position – different land orography – valleys, hills, mountains – and the possible presence of neighboring structures. The downward negative leader propagation and the propagation and interception of upward positive leader is taken into account.

In "fig. 7", is presented step by step the simulation stages according to [13].

The MAL method simulates the evolution of upward positive leader but neglects the natural negative discharge zigzag path, the leader from cloud to earth will follow the direction of maximum field intensity.

The lateral branches of the discharge are neglected, the model using a single channel in which the electrical charge relative to length sums electrical charge form all the branches. For this latter aspect at Renardieres data were obtained by triggering the discharge using a small long front positive pulse at the right electrode [14].

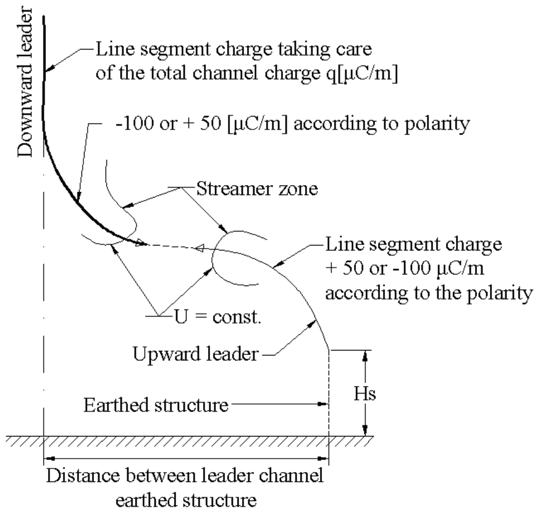

Fig. 7 Step by step layout for leader channel simulation according to [13].

Because downward leader trajectory bands, the ground protective distance PDg is smaller compeering with lateral distance LD in advancement leader model MAL. Differentiation is more important for higher protective elements and more obvious for smaller currents.

Changes in descendant trajectory resulted are used to determine the protective ground distance (PDg) – "ant protection".

Starting from lateral distance (LD) definition, according to current magnitude, the area exposed on both sides of the *L* length conductor is obtained.

Equation (4) may be used.

$$A_e = 2 \cdot L \int LD(I) \cdot p(I) dI \qquad (4)$$

Considering $L = 1m$ according to [11] is possible to determine area in relation with conductor height (*h*).

IV. MAL APPLICATION CURVE

Knowing horizontal distance between downward channel and earthed structure is possible to calculate the maximum distance (LD) at which the structure is still hit and also the maximum protection distance (PDG) at ground level.

Values are increased by 10% in order to scope in to statistics the positive lightning and additionally increased to take in to account the upward lightnings.

A. Leader advancement model

Using the results published by Dellera, Diendorfer, Raschidi and Garbagnate [10] - [13], following results war obtained.

By using MAL analysis is necessary to emphasize certain aspects. Lightning channels hitting the structure are contained in a cylinder of radius, LD.

This geometry is directly influenced by the current intensity *I* and structure height; in consequence the number of incidents will be determined by these elements.

For an object of height h = 37 m, the lightning's of I = 20 kA entering into a cylinder of 31.3 m radius are important; at higher currents, I = 60 kA, the cylinder is 52.6 m radius.

From this observation it is obvious that the height of the structure will influence the number of events. Obviously a quantitative analysis should use also the probabilistic distribution curve for this phenomenon.

Object height influence represents the great progress of the methods. Approaches based on electrogeometric model don't have this possibility because the only measure involved is the lightning current.

It underlines once again that it is not about protection effectiveness well determined by striking distance and attraction radius; it is about the number of events taken in to account.

In the same way the protected distance at ground level PDg change, "ant problem". For a 37 m object, the lightning with 20 kA intensity will fall to 21.8 m and a 60 kA lightning at 41.6 m. These values are far from the famous calculation find in Romanian normative, $1{,}8 \cdot h$ which would mean 55.5 m.

A careful numerical analysis of the curves obtained by MAL, allows considering a linear dependency for independent variables *h* and *I* when calculating *LD* and *PDg*.

$$\begin{aligned} LD &= f(h,I) \\ PDg &= g(h,I) \end{aligned} \qquad (5)$$

Numerical analysis of functions with multiple variables $g = F(x, y)$, has very complex rules and restrictions.

Simple equations for lateral distance *LD* (6) and for protection distances at ground level *PDg* (7) can be propose.

$$LD(h,I) = A(h) \cdot I + B(h) \qquad (6)$$

$$PDg(h,I) = C(h) \cdot I + D(h) \qquad (7)$$

In relations (6) and (7) coefficients, can be written in the same hypothesis of linear dependence as follows

$$A(h) = \alpha \cdot h + \beta \qquad B(h) = \gamma \cdot h + \delta \qquad (8)$$

$$C(h) = \alpha_1 \cdot h + \beta_1 \qquad D(h) = \gamma_1 \cdot h + \delta_1 \qquad (9)$$

In Tables I and II are presented the results of these calculations.

TABLE I
COEFFICIENTS FOR PROTECTION DISTANCES AT GROUND LEVEL

C	α_1	β_1		
	0,011052	0,08566		
D			γ_1	δ_1
			0,04244	10,370175

TABLE II
COEFFICIENTS FOR LATERAL DISTANCE AT GROUND LEVEL *LD*

A	α	β		
	0,01054625	0,147375		
B			γ	δ
			0,3667325	6,81675

TABLE III
ILLUSTRATION FOR RELATIONS (8) AND (9) APPLICATION

I	LD		PDg	
	h = 30,5 m	h = 42,5 m	h = 30,5 m	h = 42,5 m
20 kA	27,4 m	34,3 m	20,1 m	23,3 m
30 kA	32,1 m	40,5 m	24,3 m	28,8 m
60 kA	46,1 m	58,4 m	37,0 m	45,5 m

For a quick use of previous analysis are given the diagrams for complex variation of these elements compared with the classic electrogeometric model (EGM) “fig. 8”.

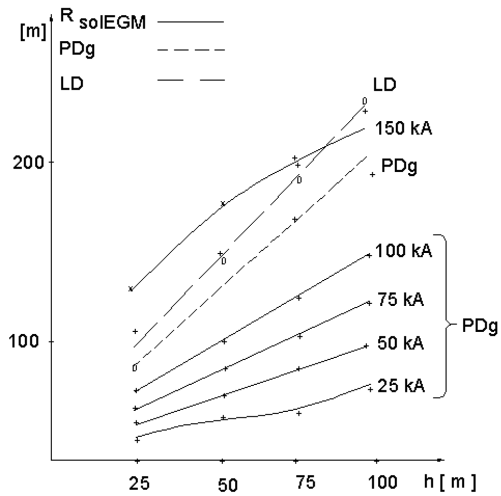

Fig. 8. The distance at ground level *PDg*, and lateral distance at ground level *LD* variation with the object high, for different currents.

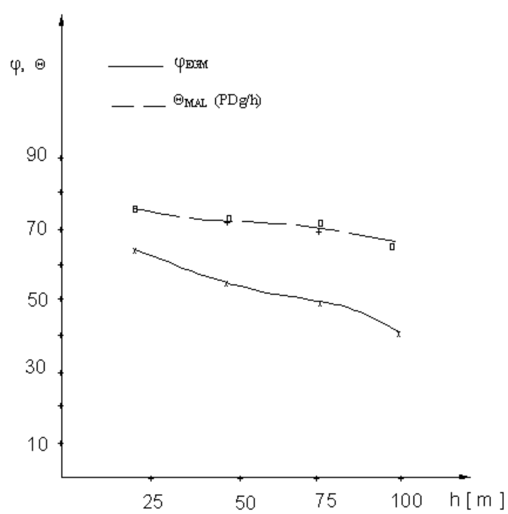

Fig. 9. Protection angle at ground level φ_{EGM} φ (EGM method), and θ for advancing leader (MAL) variation with the height of the protector.

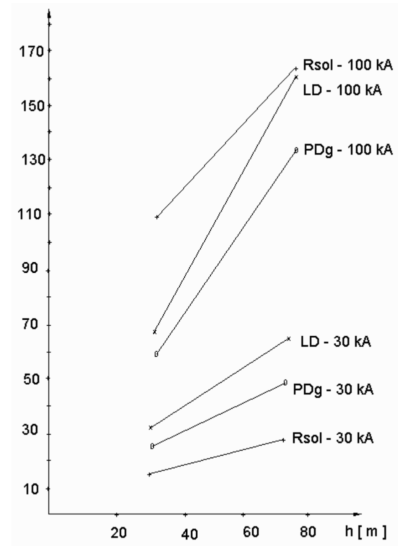

Fig. 10. PDG, LD and R_{sol} variation with the protector height for different currents.

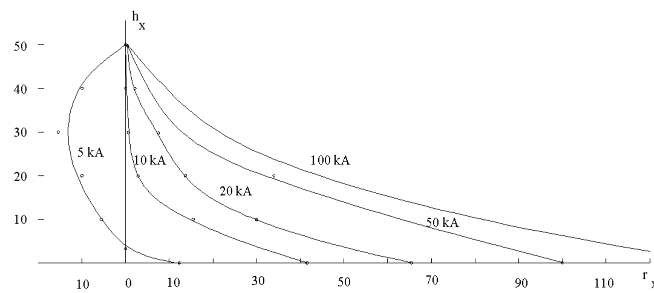

Fig. 11. Protection provided by a protector of h = 50m high for various currents, marking the distances obtained with EGM model and PDg distance obtained with LD method.

TABLE IV

1	I [kA]	150			
2	R [m]	265.3			
3	h [m]	100	75	50	25
4	φ_{EGM}	38.5 º	45.8 º	54.2 º	64.9 º
5	$R_{sol\ EGM}$ [m]	204.5	181.2	152.3	110.4
6	PDg [m]	193.2	156.7	108.2	65.7
7	LD [m]	223.8	175.1	126.4	77.6
8	for 1 lightning/km^2/year	112%	134%	198%	282%
9	φ_{EGM} classical	63.9 º	67.5 º	71.8 º	77.2 º
10	θ_{AL}	62.6 º	64.4 º	65.2 º	69.2 º
11	EGM [km^2]	30.5	27.1	22.9	16.9
	AL [km^2]	28.9	23.6	16.5	10.4

TABLE V

1	I [kA]	100			
2	R [m]	265.3			
3	h [m]	100	75	50	25
4	φ_{EGM}	30.4 º	39.0 º	48.9 º	61.2 º
5	$R_{sol\ EGM}$ [m]	172.5	154.9	130.8	95.7
6	PDg [m]	133.7	105.0	76.3	47.6
7	LD [m]	164.0	128.2	92.6	57.1
8	for 1 lightning/km^2/year	110.8%	217.6%	293.9%	404.2%
9	φ_{EGM} classical	59.8 º	64.2 º	56.8 º	75.4 º
10	θ_{AL}	53.2 º	54.5 º	56.7 º	62.3 º
11	EGM [km^2]	25.8	23.3	19.8	14.7
	AL [km^2]	20.2	16.1	11.9	7.7

TABLE VI

1	I [kA]	75			
2	R [m]	167.1			
3	h [m]	100	75	50	25
4	φ_{EGM}	23.7 º	33.5 º	44.5 º	58.3 º
5	R_{sol_EGM} [m]	151.2	137.6	117.2	86.3
6	PDg [m]	103.9	82.1	60.4	38.5
7	LD [m]	133.6	104.7	75.8	46.8
8	for 1 lightning/km^2/year	212.9%	288.5%	376.5%	502.4%
9	φ_{EGM} classical	56.6 º	61.4 º	66.9 º	73.8 º
10	θ_{AL}	46.1 º	47.5 º	50.4 º	57 º
11	EGM [km^2]	22.8	20.8	17.8	13.4
	AL [km^2]	15.9	12.7	9.9	6.4

TABLE VII

1	I [kA]	50			
2	R [m]	127.5			
3	h [m]	100	75	50	25
4	φ_{EGM}	12.5 º	24.3 º	37.4 º	53.5 º
5	R_{sol_EGM} [m]	116.4	114.9	99	67.4
6	PDg [m]	74.2	59.3	44.4	29.5
7	LD [m]	103.6	81.2	58.9	36.5
8	for 1 lightning/km^2/year	246%	375%	497%	522%
9	φ_{EGM} classical	49.3 º	56.9 º	63.2 º	69.6 º
10	θ_{AL}	36.5 º	38.3 º	41.6 º	49.7 º
11	EGM [km^2]	17.7	17.5	15.2	10.6
	AL [km^2]	11.6	9.4	7.3	5.1

TABLE VIII

1	I [kA]	`25			
2	R [m]	127.5			
3	h [m]	100	75	50	25
4	φ_{EGM}	-14.3 º	3.6 º	22.1 º	43.5 º
5	R_{sol_EGM} [m]	78.6	79.8	73.4	57.2
6	PDg [m]	44.4	36.4	29.4	20.5
7	LD [m]	73.5	57.8	42	26.2
8	for 1 lightning/km^2/year	313.4%	475.8%	623.3%	778.5%
9	φ_{EGM} classical	38.2 º	46.8 º	55.7 º	66.4 º
10	θ_{AL}	23.9 º	25.8 º	30.5 º	39.4 º
11	EGM [km^2]	12.2	12.4	11.5	9.1
	AL [km^2]	7.3	5.5	5.1	3.8

Equations used in MEGD method are presented below; the striking distance is evaluated with (10):

$$R = 9{,}4 \cdot I^{2/3} \tag{10}$$

The horizontal angle between critical point of intersection of the R radius circle with the parable determinate by the tip of the protector and soil "φ" is (11):

$$\sin\varphi = (R - h)/R \tag{11}$$

The limit protection distance of a zero height object is (12):

$$R_{sol\_EGM} = R \cdot \cos\left[\arcsin\frac{R-h}{R}\right] \tag{12}$$

It is possible to compare "fig. 11" the protection angles at soil level "φ" determined using this method and the leader progression model (MAL).

$$tg\theta = \frac{DPg}{h} \tag{13}$$

In fig. 10 – 12 are presented the variations obtain using the previous relationships the values for protection distance of a zero height object R_{sol_EGM}, protective ground distance PDg and lateral distance LD are presented in tables IV - VIII.

Studies have been conducted for 5 currents: 150 kA, 100 kA, 75 kA, 50 kA, 25 kA and for different protection heights 25 m, 50m, 75m and 100m.

Analyzing the results we can determine that for heights less than 50 m protection efficiency increases with the height of the structure bat for heights bigger the 50 m the protection efficiency is constant.

This behavior is probably due to the mixture of electrical charge in downward channel causing the trigger or early leader's initiation due to typical field intensification for higher and slender structures.

For small currents (I < 30kA) MEG model determine smaller catchment area. For higher currents the areas are larger, for 42.5 m objects catchment area using MEG model, on entire length, is (14):

$$A_{EGM} = [2 \cdot R_{sol\_EGM} + d_{cp}] \cdot l_{line} \tag{14}$$

Using lieder progression model (MAL) catchment area is (15):

$$A_{AL} = [2 \cdot PD_g + d_{cp}] \cdot l_{line} \tag{15}$$

In (14), (15) d_{cp} is the distance between protection conductors and l_{line} is 72.5 kilometers representing the total analyzed length of 220kV line Bucharest South – Ghizdaru.

V. FINAL ELEMENTS

The means of lightning protection, vertical rod and horizontal protective lines are analyzed by their efficiency, which means the protection at ground level, provided.

With this research it can be determined the impact of the new information's provided by lightning location system (LLS and ANM).

Various errors occurring in this location system, will lead to errors in angle intersection calculations, so it will be necessary to superimpose the "error ellipse" in a probabilistic analysis of multi – variable.

Also, credibility for any statistical analysis derives from quality of use information. The results in this analysis are obtained base on 3 years records. At least another two years of measurements will be needed.

TABLE IX
GROUND LIGHTNING DENSITY ALOG OHL (NO./KM^2 & YEAR)

Year / average	BUFFER					
	Along the line		Moved to west		Far of the line	
	Nr. of Events	Densit y	Nr. of Events	Density	Nr. of Events	Density
2003	260	0.82	324	1.02	467	0.72
2004	238	0.75	273	0.86	581	0.89
2005	239	0.75	271	0.85	492	0.75
Average	246	0.775	290	0.91	514	0.79
Area of incidences	317.02 km^2		317.02 km^2		652.75 km^2	

TABLE X
COMPARATION OF LIGHTNING CURRENT DISTRIBUTION (KA)

Event	All teritory	400 kV OHL	
		Normal distribution	Log Normal distribution
Singular positive	30.98	24.226	14.14 (40%)
Singular negative	25.52	19.4	17.19 (67%)
Multiple negative-first component	28.74	21.94	20.62 (78%)
Multiple negative – all components	24.34	20.51	19.42 (82%)

This more detailed research will provide an explanation for the low lightning probability, tables IX and X determined for Bucureşti Sud – Ghizdaru electrical line.

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VII. Biographies

Dorin Cristescu was born in Braila in Romania, on 1935. He graduated from the Polytechnic Power Engineering Institute, Bucharest, and Faculty of Mathematics, Bucharest. In university career he become professor to High voltage, Electrical power systems and Modern insulation coordination methods. His special fields of interest included: corona discharge, electric field measurement, insulation coordination and lightning protection.

T. Leonida was born in Brasov in Romania, on October, 1979. He graduated from Power Engineering Faculty, Bucharest, Romania in 2004. In the same year he joined PEF where he is presently teaching assistant. His technical interests are electromagnetic compatibility, high voltage and electrical equipment. He is preparing his PhD. thesis in the field of electromagnetic disturbances.