THE ELLIPTIC MODEL IMPLEMENTATION FOR THE ESTIMATION OF THE VERTICAL RODS' PROTECTION ZONES

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REZUMAT. Metoda sferei fictive este una dintre cele mai folosite tehnici pentru dimensionarea sistemelor de paratrăsnete din staţiile de transformare. Deşi frecvent utilizată, această metodă ignoră o serie de parametri cu o importanţă semnificativă în procesul de orientare a liderului descendent către obiectele de pe sol, astfel încât zonele de protecţie determinate au dimensiuni nerealiste. Pe baza unor rezultatele experimentale de dată recentă, în această lucrare este propus un model eliptic pentru determinarea zonelor de protecţie a sistemelor de paratrăsnete verticale.

Cuvinte cheie: trăsnet, orientare, sfera fictivă, model eliptic

Abstract. Rolling sphere method is nowadays one of the most popular methods used for dimensioning the lightning rod protective system of power stations. Although very used, this method neglects some of the most important parameters of the lightning attachment process to grounded objects thus resulting unrealistic dimensions of the protective zones. Based on recent experimental studies in this paper an elliptical model is proposed in order to estimate the lightning rods' protection zones.

Keywords: lightning, attachment, rolling sphere, elliptic model

1. INTRODUCTION

The lightning protection of power systems' installations against direct strokes is of great concern due to the major implications related to such events. By their nature, the power systems' installations are highly exposed to lightning strokes. Direct implications may consist in destroyed equipments, maintenance costs, system stability, and power outages related costs. Thus all these aspects must be considered when the power installations' lightning protective system is dimensioned. The minimum risk of direct lightning strokes in the active parts of power installations' is expected when the protective zones given by the lightning rods and/or ground wires systems, covers all of those active elements. In such circumstances, the precise calculation of the protective zones is one of the most important stages in the power systems' design.

In this sense, one of the most effective methods is the rolling sphere method, RSM, which is based on electro-geometrical theory. The main hypothesis of the method is based on the idea that the lightning strikes the nearest object on the earth situated at the so-called orientation distance from the descending leader's head. Thus, one can imagine one sphere which is moving towards the ground and which has the radius equal with the orientation distance. The head of the descending leader is considered to be in the center of this sphere. The first object touched by this virtual sphere will be stricken by the lightning.

As the striking distance value is related with a single parameter, namely the lightning current intensity, as shown by several well known empirical equations, the implementation of the rolling sphere method is quite facile and convenient. The obtained protected volumes are considered efficient for lightning currents that exceeds the value of protection current used for the striking distance estimation.

By considering only the value of the lightning current and neglecting the entire physics of the lightning attachment process the rolling sphere method is considered by some researchers nothing more than a geometrical construction method for the placement of the air terminal systems [1].

In the past two decades and mostly in recent years the knowledge over the entire process of the lightning attachment to grounded objects has significantly improved, the final stage of the lightning discharge being described through a series of new mathematical models, even more complex, known under the name of leader progression models, such as the Dellera and Garbagnati model, Rizk model, and the most recent model were proposed by Beccera and Cooray (2006), Ait-Aimar and Berger (2009) and Rizk (2010).

Even so, based on tradition the rolling sphere method is still used as it is recomended in prestigious standards like IEEE [2] and IEC [3].

2. THE BASICS OF THE ELLIPTIC MODEL

As stated before the rolling sphere method as it used today neglects some parameters which have an important influence on the lightning attachment to the grounded structures, such as lightning discharge polarity and grounded object height. Another simplifying assumption made by the rolling sphere method is that the striking distance to the ground (noted with *D*) is equal with the striking distance to masts and ground wires (noted with *S*). This idea led to the circular cone shape of the protection volumes.

Such differences regarding the striking distance to ground, masts or wires were made since the early stages of the electro-geometrical theory development by Armstrong, Brown, and Whitehead [4], [5], but only in the late '80 a revised electro-geometric (EGM) model was proposed by Mousa and Srivastava. The revised EGM model is now recommended by IEEE Standard 998 [2].

In fact the revised EGM model proposed by Mousa and the early works of Armstrong, Brown, and Whitehead suggest that the striking distance to masts, *S* is actually larger than the striking distance to ground, *D*, as shown from the general equation presented below:

$$S = k \cdot D \tag{1}$$

where:

D – striking distance to ground plane;

k –1 for strokes in wires and ground plane;

–1.1 for strokes in masts (according to Armstrong, Brown, and Whitehead [4], [5]);

–1.2 for strokes in masts (according to IEEE Std.998 [2]).

Recently, experimental studies on scale models [6], [7] have proved that indeed the striking distance to ground is not equal with striking distance to masts thus supporting the hypothesis considered in the early stage of the EGM model and his revised version recommended by IEEE.

When considering the aspects presented above, one can notice that the protective volumes boundaries are no longer determined by circles (spheres) having the radius equal with striking distance, as assumed by RSM, instead an ellipse (ellipsoid) should be used.

Although the idea of an elliptical model for the estimation of protected volumes in case of lightning is not new, first attempts in this sense being conducted by Mladenovic [8] in the early '90, the model was not further developed and implemented as the international standards continued to recommend the rolling sphere method.

In light of recent experimental and analytical studies conducted by Grzybowski [7] the elliptical model was reviewed considering the discharge polarity and grounded rod height influence on the lightning attachment process, which previously have been neglected by the RSM.

The basic configuration used by Grzybowski to determine the striking distance toward a Franklin rod is presented in Fig.1, where *H* is the height of the rod, *L* is the horizontal distance between the rod and the live electrode modeling the downward leader, *S* and *D* representing the striking distances towards the grounded rod and ground plane.

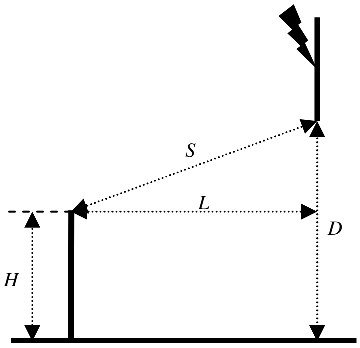

Fig.1. Basic configuration for striking distance of the Franklin rod

For both positive and negative polarity of the simulated lightning discharge Grzybowski obtained the following equations for the striking distance, *S*:

Negative: $$S = D \cdot (1 + 0.24 \cdot e^{-H/D}) \tag{2}$$

Positive: $$S = D \cdot (0.8 \cdot e^{-0.125 \cdot H/D} + 0.17) \tag{3}$$

One of the most important observations made by Grzybowski was that the lightning discharge polarity has a significant influence over the striking distance.

As it can be noticed from (2) and (3) the striking distance to the vertical rod is greater than the striking distance to ground in case of negative lightning discharges, $S > D$, and vice versa for positive lightning, $S < D$. Similar results were obtained by Mikropoulos and Tsovilis in their experimental studies [6].

When considering these aspects the elliptic model implementation for a Franklin rod is graphically represented in Fig.2 for the case when $H = D$.

As it can be observed the protected volume of a grounded rod is smaller in the case of a positive lightning discharge than for negative lightning. A conservative approach would suggest that the elliptic model for positive lightning should be used for power stations' lightning protective system designing. For both positive and negative lightning the downward leader is considered in the ellipses' center.

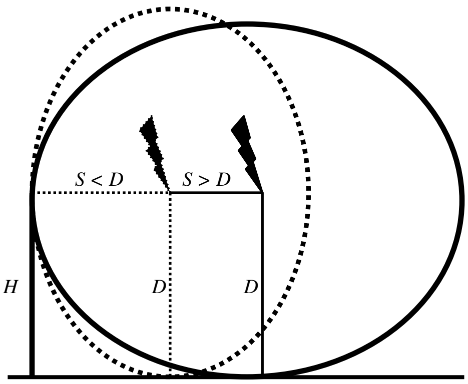

Fig.2. Elliptic model of for a vertical rod in case of positive (dashed line) and negative (continous line) polarity of the lightning discharge, $H = D$

Although when it comes for lightning protection a conservative approach is generally recommended, dimensioning the power stations' lightning protective system with the positive elliptic model would require first an analysis over the positive lightning occurrence probability in the specific area of the analyzed power station. Also, for the established occurrence probability of the positive lightning the risk of attachment to the power stations' live installations must be determined.

Such a conservative approach can be restricted by the impossibility of installing the air terminals in the needed spots due to power stations' constructive limitations, or the risk of an oversized lightning protection system with its related costs should be considered.

Since more of 90% of all lightning discharges are negative ones, the negative elliptic model should generally be used. For particular cases tough, the positive elliptic model can be considered.

The fully description of the negative elliptic model will be presented below.

3. THE NEGATIVE ELLIPTIC MODEL FOR VERTICAL RODS

When designing the lightning protection zones with the negative elliptic model the following aspects must be considered:

A. The influence of the vertical rod height

The vertical rod height influence is considered through the value of H / D ratio. The protected volume designed with the negative elliptic model can be analyzed from the general representation from Fig.3.

The general equation of the ellipse presented in Fig.3 is written below:

$$\frac{(x-a)^2}{a^2}+\frac{(y-b)^2}{b^2}=1 \tag{4}$$

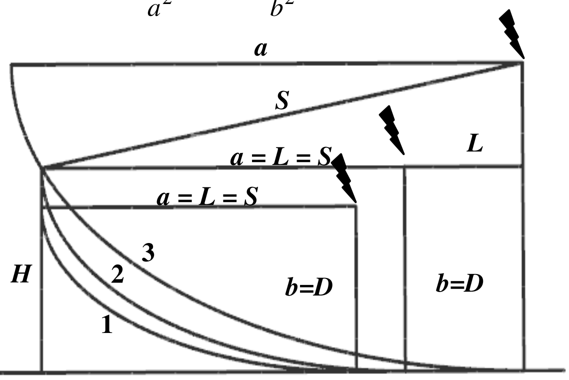

Fig.3. Elliptic model for a vertical grounded rod when: $H>D$ (curve 1), $H=D$ (curve 2), $H<D$ (curve 3)

where: a, b - the long and short arm of the ellipse.

According to Fig.3 when implementing the elliptic model the following hypothesis can be considered:

1. Case of $H > D$ ($H/D > 1$)

In this situation the long arm of the ellipse is equal with the striking distance, $a = L = S$. The short arm of the ellipse is considered as the striking distance D. As it can be noticed the concept of the useless height of the vertical rod appears for the elliptic model, similar to case of rolling sphere method. Thus the active height of a vertical air terminal will be equal with striking distance to ground, D. The boundary of the protected zone is represented by the curve 1.

2. Case of $H = D$ ($H/D = 1$)

Comparing with the first case presented above similar remarks can be made, as the long arm of the ellipse is equal with the striking distance, $a = L = S$. Yet in this situation the concept of useless height of the rod is not supported as the entire length of the air terminal is involved in the lightning attachment process. The protection zone is delimited by the curve 2 from Fig.3.

3. Case of $H < D$ ($H/D < 1$)

This is practically the most common situation for the case of power stations' lightning protective system. The ellipses' long arm length can be determined with the following relation:

$$a = D\cdot\sqrt{\frac{S^2-(D-H)^2}{D^2-(D-H)^2}} \tag{5}$$

The lateral distance between the vertical rod and downward leader is obtained as following:

$$L=\sqrt{S^2-(D-H)^2} \tag{6}$$

The protection zone boundary is given by the curve 3 in Fig. 3. For all cases presented above the short arm of the ellipse is represented by the striking distance to the ground, $b = D$.

B. The dimensions of the protected volume

1. The case of a single vertical rod

For a single vertical rod the dimension of the protected volume must be known at the ground level and at different H_x height, depending on the height of the object to be protected.

At the ground level the length of the protected area L_0, is equal with the lateral distance between the vertical rod and downward leader, L. For the case of $H > D$ and $H = D$ dimension L_0 is equal with the striking distance to the grounded rod, S. When $H < D$ the dimension of the protected zone at the ground level is given by relation (6), presented above.

The protection of a certain H_x height object against direct lightning strokes will be ensured only if the object is placed at a L_x distance from the vertical rod, as presented in figure below:

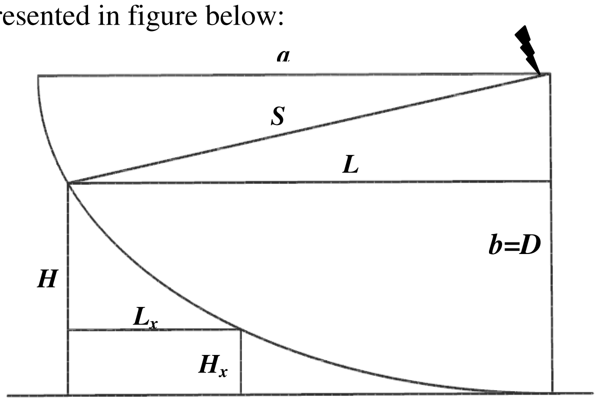

Fig.4. The lateral protection distance for a grounded object of H_x height

For estimating the lateral distance L_x at which a grounded object having an H_x height is protected by the vertical rod, the ellipses' general equation (4) is put in the following form:

$$x^2 - 2 \cdot a \cdot x + c = 0 \qquad (7)$$

where: $c = \frac{a^2}{b^2} \cdot (H_x - b)^2$

The value of the lateral distance L_x can be determined using:

$$L_x = x_2 - (a - L) \qquad (8)$$

where: x_2 is the second root of equation (7).

If $H \geq D$ then $a = L$, and $L_x = x_2$.

2. The case of multiple vertical rods systems

In case of power stations the protection zone estimation is realized by considering groups of two, three or four vertical rods. The protection zone of a multiple rod system consists in two major areas: the outer side of the multiple rod protection system and the area between the vertical rods.

The outer protection zone can be determined by implementing the elliptic model for each vertical rod alone, as previously described.

When designing the inner protection area using an ellipse for two vertical rods systems or ellipsoid for three or four vertical rods systems several remarks must be made.

For a given multiple rod system to have a common protection area the following condition must be fulfilled:

$$H_{min} > 0 \qquad (9)$$

where H_{min} is the minimum height between the rods.

Condition (9) can be customized according to number of vertical rods considered, as written below:

$dx < L_0$ – for two vertical rods;
$R_0 < L_0$ – for three vertical rods; (10)
$D_0 < L_0$ – when four rods are considered;

where:

dx – is the semidistance between two rods;
R_0 – the circumradius of the triangle in case of groups of three rods;
D_0 – the rectangle's semidiagonal when four rods are considered.

It must be noted that these deductions were made considering that the vertical rods have the same height.

If the analyzed group of vertical rods does share a common protection zone another important parameter to be determined is the minimum height of that common protection area, noted with H_{min}. In order to determine the value of this key parameter several remarks must be made regarding how the inner protection area between multiple rods is obtained using the elliptic model.

When an ellipse is used to determine the inner protection zone of a multiple rod system the striking distance to rods, S, must have the same value as used to determine the outer protection area of the rods. In this sense the upper ellipses' center precise location must be determined. This can be achieved as presented in the graphical representation from Fig.5.

In order to maintain the same striking distance to the rods, S, the ellipses' center is located at a H_x height above the height of the rods, H. H_x height can be determined according to the following relation:

$$H_x = \sqrt{S^2 - dx^2} \qquad (11)$$

Although the same striking distance to grounded rod is kept, the upper ellipse which generates the inner protection area of the rods have different dimensions than the ellipses used to determine the outer protection area boundary.

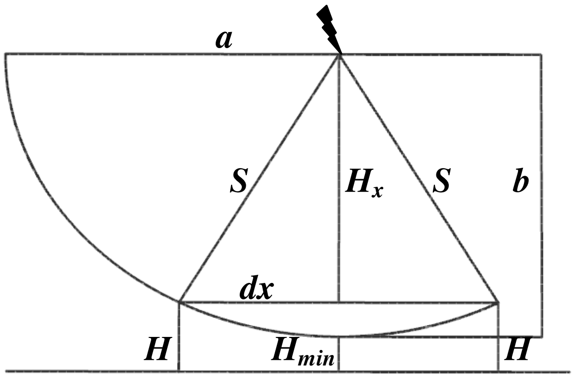

Fig.5. The inner protection zone estimation for two vertical rods

Keeping the value of ellipses' long arm, *a*, constant as previously determined, the ellipses' small arm length, *b* results from the following expression:

$$b = \sqrt{\frac{y^2}{1 - \frac{x^2}{a^2}}} \tag{12}$$

where *x* and *y* are the coordinates of one of the vertical rods' tip. If the upper ellipse's center represents the coordinating system's center, then *x* and *y* from (12) are equal with ± *dx* and - H_x respective.

The lowest point in the inner area between two rods at which the protection against direct strokes is ensured is at H_{min} height which can be determined as following:

$$H_{min} = H + H_x - b \tag{13}$$

This relation can also be used for groups of three or four vertical rods as long as instead the semidistance *dx*, the circumradius R_0, or the rectangle's semidiagonal D_0 are used.

As the distance between the rods is incresead the upper ellipses' long arm value is decreasing until at the limit when $dx = L_0$ the value of *b* is equal with the striking distance to the ground, *D* thus $H_{min} = 0$ and the multiple rod system doesn't share a common protection zone.

4. CONCLUSIONS

✓ Recent experimental studies [6], [7] on the lightning attachment process to grounded rods proved that the striking distance to ground plane is not equal with the striking distance to the rod, as the rolling sphere method assumes. This led to the idea that an elliptic model should be used when estimating the lightning protection zones. Although the idea of an elliptic model is not new, in this paper the elliptic model was revised and improved.

✓ The experimental results suggest that the lightning polarity is a key factor as the protection zones obtained under positive lightning are considerably smaller that the ones obtained for a negative discharge. This result must be balanced with the occurrence probability of positive lightning. The authors focused their attention on the negative elliptic model as the negative polarity of the lightning discharge is the most common.

✓ The protection area's graphical construction rules were established for single vertical rods and multiple rods systems. Mathematical relations for calculating the dimensions of the protected volumes were established as well.

✓ Although the elliptic model can still be considered a geometrical construction model, in light of recent experimental studies it is believed that this model is developed on more realistic basis than the rolling sphere method and it can be used for the power stations' protection zones estimation.

✓ Comparative analysis between the rolling sphere method and elliptic model must be conducted for practical cases like power stations. These aspects will make the object of a further study.

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