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The protected space proved to be an undefined term

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***Abstract*— The protected space is not really protected against penetration of lightning. Probability of interception failure cannot be related to parameters of the protected space without considering the structure to be protected. Therefore, the term ”protected space” cannot be exactly defined.**

Keywords-lightning stroke; lightning interception; protected space; protection angle; rolling sphere;

I. INTRODUCTION

At the beginning, a primitive idea existed that the corona discharge on a pointed lightning rod could neutralize the electric charge of the cloud, and so prevents the development of the lightning flash. Therefore, the peak of rod was protected against corrosion by gilding.

The protective effect of a lightning rod was expressed by a protected area around it, whose radius is related to the height of rod. Because this area is defined only in the case of horizontal plane, protection angle was introduced later; whose tangent equals to the ratio of the horizontal extension of the protection to the height of the lightning rod. The space under this angle was taken as protected space or protected volume.

Because lightning strokes occurred also near the lightning rods, their protective effect became doubtful at the end of the 19th century. Therefore, the Faraday cage spreads as typical air-termination of buildings and similar structures [1]. In this case, the protected space cannot be interpreted, but the mesh wide of the air-termination network became relevant. In the same time, the application of lightning rod became to be avoided in some countries (e.g. Germany [2]).

The protected space became interesting again with spreading the electrical transmission lines at the beginning of 20th century. The lightning protection of these lines could be favorably handled with the protection angle, because of their simple two-dimensional arrangement. At the beginning, protection angle of 45° was introduced, which decreased later with increasing heights of transmission lines.

The research of the striking process resulted in more sophisticated determinations of the protected volume in the middle of 20th century.

II. ESTIMATION OF THE PROTECTED VOLUME

A. *Development of estimation*

Before discovery of development the lightning flash, the observation of lightning strokes gave information alone about the protective effect of lightning air-termination. Until 1930, no other possibility was available for this purpose.

The high voltage impulse generators made possible to perform scale model experiments with discharge of about 1 m long. Such experiments marked the decade after 1930.

About ten years later, Golde [3] determined the relation between the striking distance and the lightning current, which concluded to the electro-geometrical model.

Hungary standardized the rolling sphere method in 1962, and then the rolling sphere theory was worked out in several steps.

The computer technology made possible the simulation of the lightning process, which was applied to estimate the protection volume.

B. *Result of observed lightning strokes*

Benjamin Franklin supposed that the protective effect of a lightning rod extends to the same distance as its height. This based more on intuition than observing many strokes. It corresponds to protection angle of 45° although that was recently used too [4]. In the following 150 years, many experts tried to estimate the extension of protective effect of a rod, and Schwaiger [5] collected their results in a table [6]. According to this table the protection angle may be between 7° and 83°; therefore, this is a hopeless method to find a relevant value. The cause of the fiasco is the great difference of geometrical situations and lightning parameters at each observed lightning stroke. Additionally, there was almost no possibility of communication between the experts.

The high voltage lines offered suitable conditions for application of this method. They have a very simple geometrical structure that makes possible a two-dimensional handling. Considering their huge length all over the world and more than 100 years operation have produce enough experience to estimate the effective protection angles.

TABLE I. CHANGING THE ACCEPTABLE VALUES OF PROTECTION ANGLE

Some typical pictures				
Epoch	1910-1920	1930-1940	1950-1960	after 1970
Voltage	10-20 kV	100-220 kV	300-400 kV	above 500 kV
Height	10-15 m	20-30 m	30-40 m	above 50 m
Protection angle	45°	30°	20°	15°

During this time, the transported energy, the applied voltage and the height of the lines were continuously growing that required to decrease the applied protection angle. Acceptable values are shown in Table I. These are not exact results of statistical evaluation, but electric power networks sufficiently operated with these protection angles. The annual frequency of shielding failure was about 0.1 per 100 km.

C. Scale model experiments

The multistage impulse generators could produce discharges up to 1 m length in the laboratory since 1933. This initiated the idea that the problems of lightning interception can be solved by scale model experiments [7]. However, a difficult question rose just at the beginning. If the experiment aims modeling the lightning channel from the cloud to ground, the scale should be about 1 to 1000, which results in some cm high models of structures.

In the meantime, intensive research work was going in South Africa [8, 9], which detected with records of Boys-camera that the downward leader stochastically propagates in its upper part and the point of strike will be determined near the earth. Therefore, the upper part of the lightning path was usually modeled with a metal rod. However, the position of its bottom end remained open question [10].

The model experiments were performed further, but the height of the energized electrode does not equal to the scale of structures [11]. Some experiments try to model also the stepwise propagation of the downward leader, but with low success [12]. Results of model experiments were not evidently accepted [13] and Golde finally stated the limited validity of the scale model experiments [6].

Taking another way of research, Schwaiger tried to determine the worst place of the striking point. This is the place, where the head of downward leader is, when the point of strike becomes determined. The striking point must be distinguished from point of strike, where the lightning attaches a structure or the ground. This is illustrated by Fig. 1. With other words: the lightning turns at the striking point toward the point of strike. They are separated from each other with the well-known striking distance.

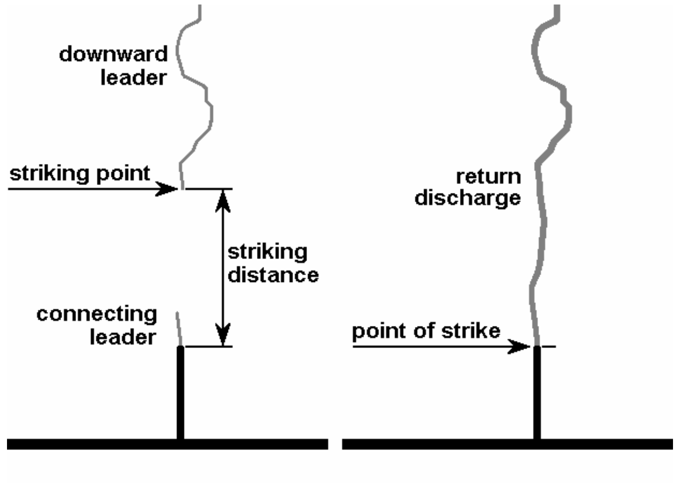


Figure 1. Definition of striking point and point of strike

As a first idea, Schwaiger supposed that the worst position of the striking point could be in the height equal to the height of the actual structure [5, 14]. This supposition based on photos which shown sometimes significant (90°) inflexions in this heights. His system was related only to transmission lines, which can handled as two-dimensional systems. The protected space was bordered by circular arcs, whose centers were in the height of the structure (usually the air termination wires) and they can have several radii as shown in Fig.2*a*. He has never tried to apply this system for three-dimensional problems; therefore, the circular arcs are not rotated around a vertical axe, which would produce a sphere. Verebélÿ proved Schwaiger's system with scale model experiments and sunk the centers of the circular arcs with 10% of their radii [15].

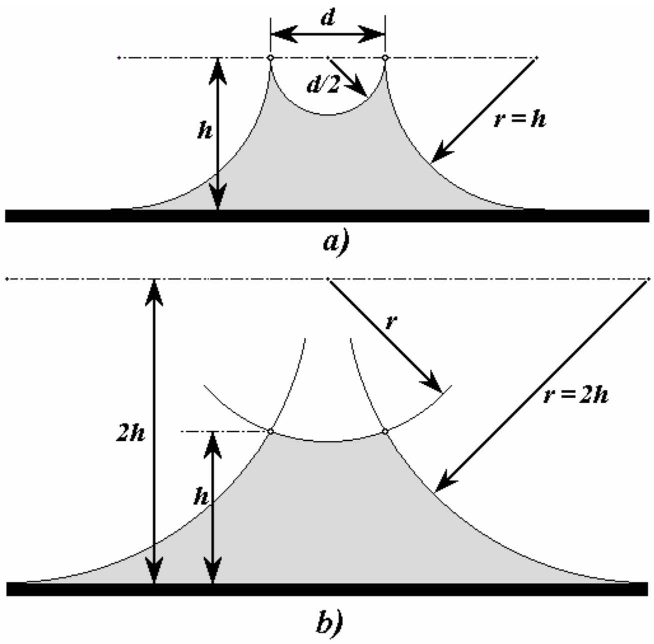


Figure 2. Construction of protection space with circular arcs; *a)* According to Schwaiger; b) With elevated centers of the arcs.

Schwaiger's system proved to be excessive for practical application; therefore, the height of the centers was taken in elevated height as shown in Fig, 2*b*. Without any scientific basis, the supposed arbitrary values were about twice or thirds the height of structure [16, 17]. The circular arc was replaced also with other curves to bordering the protected volume [18].

D. Relation between striking distance and lightning current

Instead of such guessing, Golde worked out a relation between the striking distance and the peek value of the lightning current [18]. This based on the supposition that the downward leader is just in the striking point, when the first connecting leader started towards it. This depends on the charge deposed along the leader channel, because this charge determines the lightning current as well. The correct mathematical formula of the relation between the striking distance (r) and the lightning current (I) is as follows:

$$\left(\frac{r}{r_m}\right)^p = \left(\frac{I}{I_m}\right). \qquad (1)$$

In this formula r and I are the actual, while r_m and I_m the median values of the striking distance and the lightning current respectively. According to the diagrams by Golde [18], the exponent is assumed $p \cong 1.33$ (4/3). Several authors found $p = 1.25...2.0$, while recently, $p = 1.5...1.67$ is usually assumed.

This relation gave the base of the electro-geometrical model, which made the protected space a function of the lightning current [19, 20, 21]. Using the statistical distribution of lightning current, a possibility was opened to estimate the efficiency of the interception [22, 23]. An application of the electro-geometrical model is the rolling sphere method too.

Golde and many other experts studied only two-dimensional problems of the transmission lines, so this relation resulted only in circular arcs.

E. The rolling sphere method

The rolling sphere method was first time introduced in the Hungarian Standard of lightning protection in 1962. It was an expansion of Schwaiger's two-dimensional system (see II/*C*) to three-dimensional application. The radius of sphere was assumed equal to step of downward leader; namely 15 m (as minimum) and 50 m (as average). It was taken nothing more than a construction method for positioning air-termination systems in the case of danger of explosion. First time, Hösl [24] reported about this method in 1971, giving a review over some national standards. Some study dealt with the idea of this method in USA in the early 1970s years. These first publications assumed no radius of sphere. They used first time the name: „rolling sphere" [26].

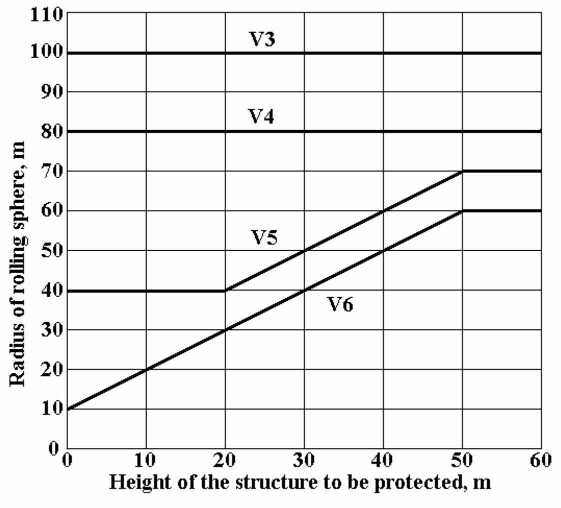
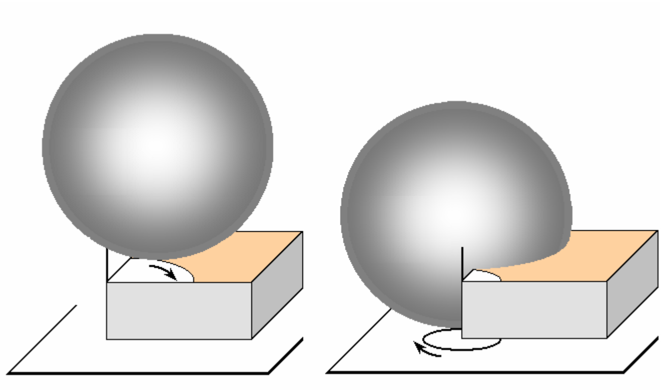


Figure 3. The radius of rolling sphere according to the Hungarian code of lightning protection

The Hungarian code was modified in 1972 and 1982. Fig. 4 plots the radii of rolling sphere according to the protection level marked by V3...V6 [25]. Since the second date, these radii of the rolling sphere were used for construction of air termination systems until the introduction of IEC-EN 62305 standards in 2009. During these 27 years, no considerable damage was recorded in Hungary that has been caused by interception failure.

It should be remark that the rolling sphere method is often used false. According to the definition of the rolling sphere method in IEC-EN 62305-3: the sphere may touch only the ground and/or the air-termination system. Fig. 4*a* shows an often occurring false application of this method, in contrast to Fig. 4*b*, which illustrates a correct application [27].



a) b)

Figure 4. False (*a*) and correct (*b*)application of the rolling sphere method

Fig. 4*a* shows a detail of Figure E.19, which can be seen in IEC-EN 62305-3 standard Annex E. The sphere moves on the surface of the roof continuously touching it. This is inconsistent with the referred definition, which allows touching only the ground and/or air-termination. According to correct application, the sphere is rolling on the ground and results in a considerable smaller protected area of the roof, as shown in Fig. 4*b*. In this case, the sphere can penetrate into the structure to be protected and shows that a great part of the structure is not protected against lightning stroke.

F. Confused relation between the protection angle and the rolling sphere methods

According to IEC-EN 62305-3 standard, an air-termination system is adequate, if it is constructed with protection angles using the diagram shown in Fig. 5.

Figure 5. Protection angle according to IEC-EN 62305-3

Although, it is not mentioned, but this diagram origins from a confuse assumption. This is based on supposition that either the protection angle or the rolling sphere produces equivalent protection levels, if A_1 and A_2 areas balance each other in Fig. 6 [8]. However, these areas have no physical sense; therefore, this idea is a simple inanity.

A very important contradiction is between the standardized protection angles and the experience obtained by operation of high voltage lines illustrated in Table. I. The height means in Fig. 5 the vertical distance between the earth wires and the conductors to be protected. This is usually in range of 5–10 m depending from the applied voltage. While higher than 45° or sometimes 70°–80° angles belong to these heights in the diagram, the experience resulted only in angles under 45°. The minimum protection angle is 23.23° in Fig. 5 in contrast to angles of 15°–20°, which are used at UHV lines all over the world. Other arguments are detailed in [29, 30]. Protection angles of 70°–80° suggested using only one air-termination device that resulted in unconventional lightning protectors.

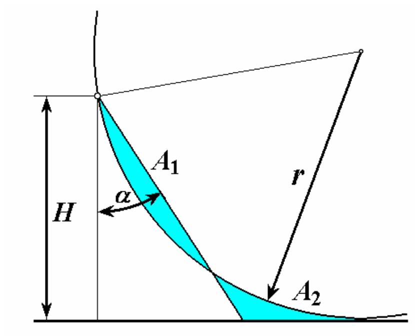


Figure 6. Supposed equivalence of protection angle and rolling sphere

G. Protection volume of ESE lightning protectors

Early Streamer Emission (ESE) has been detected before the breakdown in high voltage laboratory. This streamer type discharge differs from the connecting leader because no thermoionization is in process. Notwithstanding, the ESE technology takes it so as connecting leader. The promised protected volume is developed according to the steps indicated by Fig. 7.

The physical height of the protector determines a protection angle that is usually about 60°–80° using the diagram of Fig. 5. This is shown with black lines in Fig. 7.

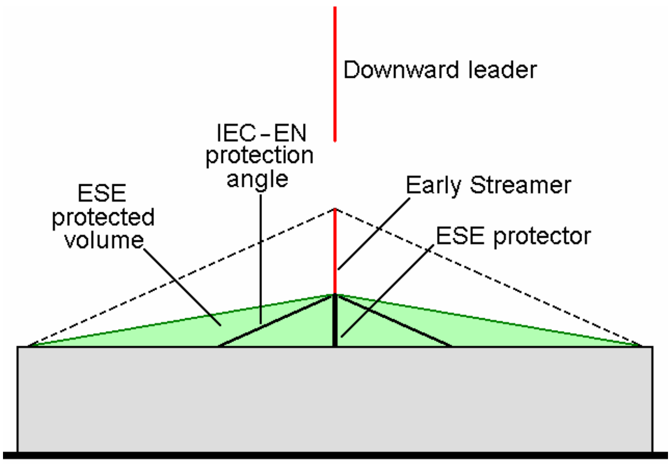


Figure 7. Protected volume by ESE concept

It is supposed that early streamer starts from the peak of the lightning protector, when a downward leader approaches. This streamer discharge is considered as an elongation of the protector. Therefore, the protected volume has been elevated to the virtually height that is indicated with dash lines. This is only a virtual protected volume, because producing any protective effect by ESE protector above itself would be absolute irrational supposition. However, the ESE business offers the green marked protected volume (Fig. 7) referring to the horizontal extending the virtually protected area. The protected volume of ESE protector is based on the large protection angles according to the IEC-EN 62305-3 standard, which is also dubious.

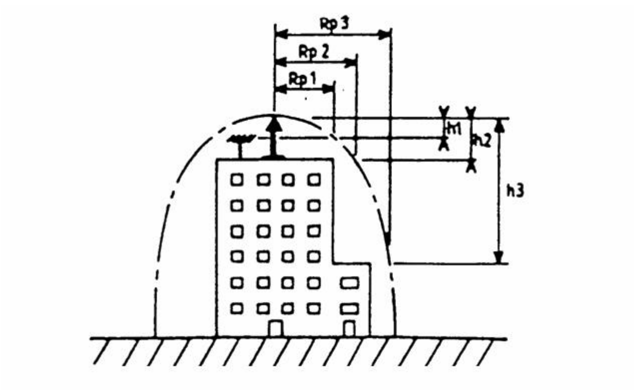


Figure 8. ESE protected space in the French Standard [31].

The previous explanation is valid only at the top of the protected space of ESE devices according to the French Standard FN C 17-102 (Fig. 8). In other case, the complete form is similar to the protected space of the radioactive protectors reported about 50 years ago.

III. General Problems of the Protected Space

The protected space or protected volume is bordered with a surface that is usually derived from a straight line (e. g. protection angle) or a circular arc (e. g. rolling sphere). Sometimes, other forms also occur (e. g. ESE). The space or volume can be correctly defined by geometrical rules. In contrast, the definition of protection causes several problems.

A. Is the protected space really protected?

There is a general problem concerning the protected space that the empty space is never struck by lightning, but the point of strike is always on a structure or on the ground. Therefore, the protection of any space is an irrational topic.

A more exact question would be: Is a structure perfectly protected against direct stroke inside the protected space? However, many lightning strokes were observed on the side of high towers as the Ostankino television tower in Moscow and the CN Tower in Toronto.

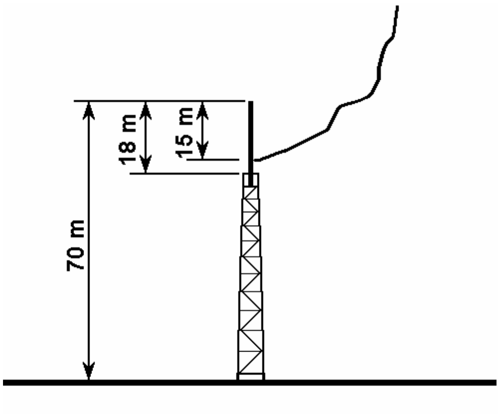


Figure 9. Lightning stroke on the side of a rod

A most surprising lightning stroke happened on Monte San Salvatore (Switzerland) [32]. The upper section of a tower consisted of an 18 m long iron tube, whose side was struck by lightning on July 29 1953. As shown by Fig. 9, the point of strike was at 15 m below the top. This stroke has been recorded with Boys-camera and on a photo. It is generally accepted nowadays that no perfect protection can be supposed against direct stroke. Thus, protection of 100% never exists.

B. Is a uniform protection level inside the protected space?

Because the air-termination system can never produce the protection of 100%, it is supposed that the protected space represents a lower level. This could be valid only in the case, if a uniform protection level exists inside the protected space independent from the form and position of the structure to be protected.

The several definitions of the protected space determine geometrical conditions, which are fulfilled on the bordering surface. For example: each point is in same distance from the center of the rolling sphere. This means a physical condition too that the striking point is equally distant from the bordering surface as from the air termination.

When a structure to be protected contacts the bordering of the protected space, the lightning strokes will be divided among the structure and the air termination. Similar situation comes into being with protection angle as shown by Fig. 10.

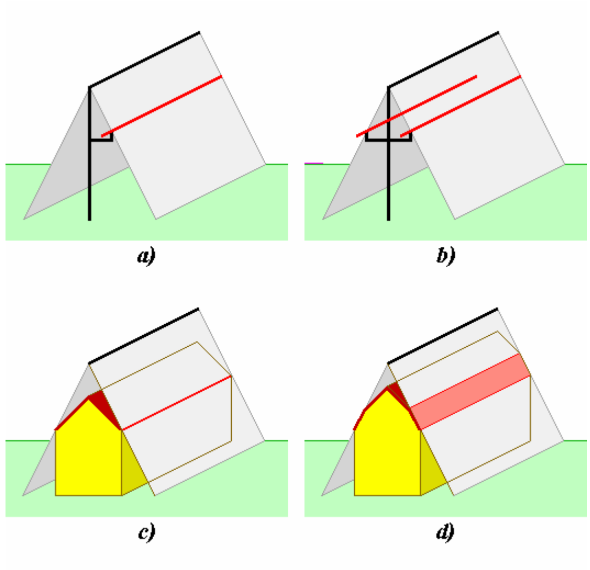


Figure 10. Contacting the bordering surface of protection space with several structures

The protected spaces are the same on each picture, but in cases *b)* and *c)* the chance of stroke is twice of that in case *a)*. In case *d)* the contact extends over an area; therefore, the chance of strike is higher than in other cases. In contrast, this chance can be considerably lower, when such a contact does not come into being at all. Therefore, the probability of a lightning stroke may be very divergent in spite of the same protected space.

C. Is the chance of interception failure determined by the radius of rolling sphere?

The striking distance is related to the lightning current according to (1). The radius of rolling sphere is usually taken equal to the striking distance. Table II shows these relations according to IEC-EN 62305 Part 1 and 3 standards. Last row is the probability of a value greater than the minimum lightning current.

TABLE II. The Parameters Related to Lightning Interception Defined for Each Protection Level

Lightning protection level	**I**	**II**	**III**	**IV**
Rolling sphere radius	20 m	30 m	45 m	60 m
Minimum peak current	3 kA	5 kA	10 kA	16 kA
Probability of greater value	0.99	0.97	0.91	0.84

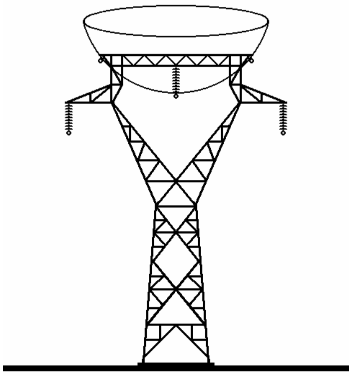


Figure 11. Application of rolling sphere on a HV line

The air-termination system should prevent the rolling sphere to move toward the structure to be protected, when the sphere just touch it. Such a case is illustrated in Fig. 11 related to the middle conductor.

When the lightning current equals to the minimum peak current (Table II), which is related to the radius of sphere, then the striking point is in the center of the sphere. The red arrow points to the striking point in Fig. 12. Lightning of higher current cannot reach the conductor to be protected. Although, such lightning occurs with probability as shown in Table II, this is not equal to the interception efficiency of air-termination system constructed with the rolling sphere method.

The striking point is somewhere in the blue marked zone if the lightning current is greater than the minimum value in Table II. The striking point falls into the green or red zones, if the current is smaller than the minimum. However, they are nearer the earth wires (air-terminations) than the conductor in green zones; therefore, these strokes will be intercepted. Thus, the probabilities give no information about either the interception efficiency or the risk of shielding failure. It can be generally stated that efficiency or risk is not determined by the radius of rolling sphere alone. By the way; those relative values (usually in percent) are undefined until 1.0 (100%) has no exact definition!

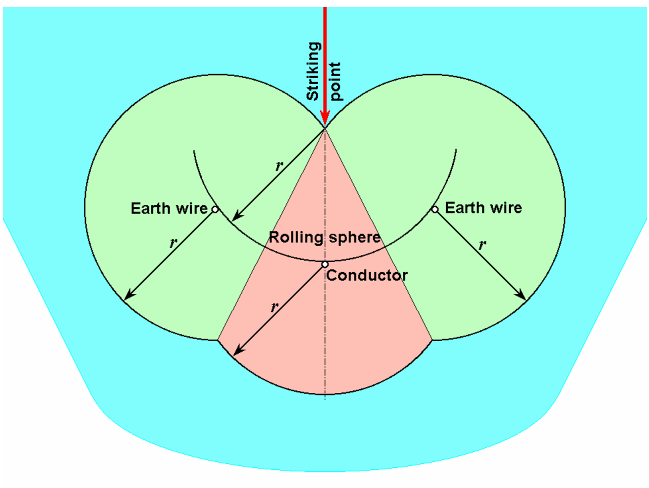


Figure 12. Zones of position of the striking point

IV. CONCLUSIONS

The words “protected space” or “protected volume” mean exactly that the lightning channel never penetrates into them. It is well known that occurring such cases could not be excluded. Many observed lightning strokes demonstrated that the lightning strikes almost anywhere with small probability at least.

Therefore, the meaning of “protected space” or “protected volume” is often so interpreted that they represent a defined probability of penetration. However, this concept has some fundamental confusion as follows:

- The lightning always strikes physical objects, but never the empty space.
- The expected frequency of lightning stroke evidently depends on the position of the structure inside the protected space. A geometrical definition of the protected space could not determine alone such a probability.
- Validity of the protected space or volume cannot be verified by experience of observed lightning strokes because of divergent arrangements and conditions.
- As an exception, the experience resulted in protection angles by long time operation of high voltage lines, which can be used in the practice.

Summing up these statements, no protected space or volume can generally represent the interception efficiency relating to a structure inside them. Therefore, it can be stated that the “protected space” or “protected volume” proved to be undefined terms.

In contrast with the previous statements, the rolling sphere, the protection angle and similar methods are necessary and important construction methods for designing air-termination systems. They could call “protection space” or “protection volume”; however, it may never believe that they represent the level of the lightning interception efficiency. This should be estimated with another method [33].

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