Lightning protection: challenges, solutions and questionable steps in the 21st century

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Abstract. Besides the special primary lightning protection of extremely high towers, huge office and governmental buildings, large industrial plants and resident parks most of the challenges were connected to the secondary lightning protection of sensitive devices in Information and Communication Technology. The 70 year history of Budapest School of Lightning Protection plays an important role in the research and education of lightning and development of lightning protection. Among results and solutions the Rolling Sphere designing method (RS) and the Probability Modulated Attraction Space (PMAS) theory are detailed. As a new field Preventive Lightning Protection (PLP) has been introduced. The PLP method means the use of special preventive actions only for the duration of the thunderstorm. Recently several non-conventional lightning protection techniques have appeared as competitors of the air termination systems formed of conventional Franklin rods. The questionable steps, non-conventional lightning protection systems reported in the literature are the radioactive lightning rods, Early Streamer Emission (ESE) rods and Dissipation Arrays (sometimes called Charge Transfer Systems).

1. Lightning protection – past, present, future
The general problem in the research of electrostatics in complicated natural and industrial systems is basically the approximation of complicated multivariable functions of input and output variables. If speaking generally about the electrostatic hazards there are two main traditional fields considering the source of the dangerous situation, namely the atmospheric electrostatics (lightning phenomenon, primary, secondary and preventive lightning protection) and industrial electrostatics (passive electrostatics – technological problems caused by static charging, fires, explosions and active electrostatics – the industrial use of electrostatic charging of materials).

The approximately 100 years research and education of Budapest School of Electrostatics were always important parts of the 228 year old history of Budapest University of Technology and Economics [15]. From the foundation of the Department of Electrical Engineering by Károly Zipernowsky (in 1893), through the research and educational work of László Verebélý, continuing the theoretical and practical results of Tibor Horváth [8,9], static electricity was and will remain in the focus.

The first records of lightning started with the early observations at the beginning of the 18th century. The first academic results were published in Buda at the end of the 18th century in German and Latin and only later in Hungarian. The 19th century brought only a few results in lightning research and lightning protection all over the world. Lightning research was started in Budapest by
László Verebély. He published the first results in the proceedings of the Hungarian Electrotechnical Association (1940) and in his inaugural at the Hungarian Academy of Sciences (1947).

The results of Tibor Horváth were summarized in Dresden (1963) and also published at the 7th International Conference on Lightning Protection (ICLP) in Arhem (1969, The Netherlands) [7]. These were the first steps of the so called probabilistic approach using the attraction volume (space) theory. The sudden use of the theory in practical life is proved by the MOSz 274 Hungarian standard of lightning protection (1952) closely followed by the next generation of the Hungarian standards on lightning protection MSZ 274 (in 1962). These periodically renewed guidelines helped the generations of lightning experts both in design and building of air termination systems. These publications back to the 60s already detailed the probability modulated attraction space theory (PMAS) and the method of rolling spheres (RS).

Generations after generations of former BSc, MSc and PhD students went on with research and education in lightning protection. Nowadays 4 generations of Budapest alma mater deliver papers on their results in international lightning protection conferences.

2. Challenges
Lightning was, is and will be one of the important challenges for mankind. Already in the early days people were faced with the problem of lightning and thunder. Explanation and ways of the protection were always important questions. One can hardly find any mythology, religion and art not trying to handle these both terrible and beautiful natural phenomena. The history of mankind is closely connected to lightning, one of the most dangerous “Acts of God”.

From the very beginning any idea of protection was extremely important. It was Benjamin Franklin, who presented our world with the so called Franklin rod (1752). He invented a fantastic tool, but the explanation of how it works was questionable [16]. (His original thought was that the lightning rod would silently discharge the thundercloud.) This problematic explanation has been the main reason of several misunderstandings and misleading steps to date.

The centuries of lightning research has always been accompanied by the research and development of lightning protection, theory and practice and the protective effect of air termination systems. The first steps of primary lightning protection were closely connected to defining the protected volume and searching the appropriate protected angle based upon the statistics of the high voltage power lines. New theories (i.e. electro-geometrical theory based on the probability approach, the attractive space concept and the accepted risk concept) and new methods (i.e. calculation of equivalent area, method of rolling spheres) have been worked out for solving basic contradictions [8].

After coming up with extremely sensitive elements and systems (informatics, communication and media) to protect information and communication systems, the secondary lightning protection theory and practice have appeared (in the second half of the 20th century). During the last decades of the same century lightning detection and location systems appeared around the world. These possibilities together with the pressure of risk management have led to the preventive lightning protection theory and practice of the last some years (see Chapter 3.3).

3. Some of the steps for solutions
3.1. Probability modulated attraction space (PMAS)
The probability-based so-called electro-geometrical method was fist published in the DSc thesis of Tibor Horváth in 1972. By the help of his theory the “annual damage frequency”, the “average strokeless period”, the “weighting factors” and the “risk of damage during time t” can be rather easily explained [8]. By the help of his calculations the residual risk of lightning can be determined in spite of the presence of a lightning protection system.

The theory is based on the physical process of lightning formation. It is well-known that the formation of a lightning stroke starts by a downward leader, which reaches a certain point called the orientation point, where it initiates an upward leader from the objects at the ground. The lightning
current starts to flow after the attachment of the leaders. The probability, that the orientation point is situated at a given distance from an object can be determined according to a distribution function [9].

Examining a certain object, there is a conditional probability, that lightning reaches the object if its distance from the orientation point has a certain value. Taking into consideration the 50% regression surface of this probability distribution, the space can be separated into two parts. The space containing those orientation points from which the lightning strike hits the object is called the attraction space. The number of expected lightning strikes can be calculated by modulating this space using the probability distribution function described in the previous paragraph.

Evaluation of the efficiency of the lightning protection system can be made by the determination of the probability modulated attraction space of the object. If having air termination system on the object, the original attraction space was reduced by the attraction space of the air termination system. From the upper part of the original attraction space all lightning strokes will not hit any more the object to be protected, but the air termination system [8, 9]. Integrating the probability distribution for the attraction space remained and multiplying it by the annual ground flash density, the expected frequency of lightning strikes hitting the building can be calculated. This is an important parameter of the risk calculation [8, 9].

The first step is to estimate the expected annual frequency of lightning that strikes the structure to be protected. This is the resulting value of two components: the equivalent area and the annual ground flash density. The equivalent area ($A_{eq}$) is defined as the area of such a field terrain, which would be struck by lightning with the same frequency as the structure to be protected. It is connected to the structure independent of the lightning activity in the region. On the other hand, the ground flash density ($N_g$) characterises the territory of the structure as a meteorological datum. As a result, the structure will be struck by $N_f$ number of flashes per year:

$$N_f = N_g \times A_{eq}$$

When a lightning stroke causes any damage, the consequences can be very divergent. These circumstances can be taken into account with weighting factors. The consequences of damage are also divergent, which can be expressed by weighting factors. Occurrence and weighting finally conclude at the weighted damage related to each type of damage. This involves the frequency of a strike, the probability for causing damage and the weighting of the consequences. The result of this calculation is the expected annual frequency of weighted damage ($D$).

The resulting frequency of weighted damage $D$ is an average value that expresses the danger of lightning. When there is a lightning protection system installed, its value is usually very low and cannot be easily interpreted. It is better to understand the period $T$. This is an average value, which gives no information on what should be expected in the next years.

$$T = \frac{1}{D} \text{ [years]}$$

Where $T$ is the average interval between two total weighted damages caused by lightning. This is usually too long a time, and can cause a false conclusion concerning the safety. A more comprehensive view can be obtained with further evaluation.

The lightning events are analyzed according to the Poisson process. The Poisson relations express the probability of a given number of events occurring during a given time. This calculation results in the probability called “Risk of damage”. According to the Poisson process the risk that the weighted damage occurs during time $t$ can be calculated. The simplified form of the Poisson relations expresses the probability that total damage occurs during time $t$ when $T$ is the average period of damage [9].

There is a rather new tool for solving the aforesaid problems, namely the use of soft computing methods: fuzzy logic, neural networks and genetic algorithms. The new approaches can be effectively used for both the risk evaluation of working systems (checking and auditing) and by using the predictive power of the methods for designing and planning activities both in atmospheric and industrial electrostatics. These methods were efficiently used for the handling of uncertainties in the determination of value $D$ [2].
Unlike general practice, handling of electrostatic hazards should be carried out through a specific risk management strategy. This strategy is specific not only for the examined arrangement but also for the risk taker.

Protection methods may include all the tools which are effective for tuning the level of risk taken (i.e. insurance, use of financial savings, changing the site). If the aim is to determine the level of risk of a given system the suggested method is to use a fault diagnostic system (observations, and interventions). Coming closer to the risk level, one has to determine the damage frequency. The risk caused by lightning can be calculated.

3.2. Rolling sphere method (RS)
The aim of the method of the rolling spheres is to design an air termination system in case of complex geometrical conditions. However the method is usually rather simple (especially while using computers). It is important to advise procedures for designing with the rolling sphere method in the case of rather complicated geometrical conditions to avoid the occurrence of false applications.

Applying this method, the positioning of the air termination system is adequate if it can prevent a fictitious sphere from intersecting the structure to be protected when approaching it from any possible direction. In extreme fall, the sphere may contact the structure to be protected only at a point or along a line, while rolling anyway on or around the air-termination system.

Although the radius of the sphere can be in connection with a lightning current, occurring with known probability, the radius is not really related to the interception efficiency of the air termination system. The probability of occurrence of a lightning current only expresses that a stroke of higher lightning current has to be excluded.

Of course, this does not mean that all lightning of lower current will strike the structure in the protected volume constructed with the given radius of the rolling sphere. So the probability of interception failures may be much lower (may be one or more magnitudes) than the probability related to the lightning current [11,13].

3.3. Preventive lightning protection
The original definition of preventive lightning protection [1] – as it was introduced on the 28th ICLP (Kanazava, Japan, 2006) by the researchers of the Budapest School of Lightning Protection – is as follows.

“The preventive lightning protection method means avoiding damage of a lightning strike with special preventive actions. The preventive actions can be of various types, and the primary goal of preventive lightning protection is to decrease the risk of damage due to lightning for the duration of the thunderstorm.” [3,4]

This novel approach in lightning protection uses forecasting in conjunction with preventive actions, plan both of them according to the other. This type of lightning protection, is extremely fruitful in the case of objects having a changing level of risk in time and in space (e.g. extra high towers and high buildings, airports, live line maintenance work on high voltage power lines, open air mass performances [14]).

The key to preventive lightning protection is using different forecasting governing the preventive action. The most important types of PLP systems are:

- Preventive Lightning Protection using Local Detectors (LDPLP), [5]
- Zonal Preventive Lightning Protection (ZPLP), [6]
- High Reliability Preventive Lightning Protection (HRPLP), [6]
- Fuzzy Preventive Lightning Protection (FPLP), [14].

4. Questionable steps
As it has been described in the history on lightning protection the use of the conventional lightning protection systems (air termination systems consisting of the so called Franklin rods, down conductors and grounding system) go back to the 18th century [16].
Later in the 20th century and even nowadays several types of the so called non-conventional systems appeared. Many of the lightning experts remember the “glory and fall” of the radioactive lightning rod. In his early publications of one of the “fathers of lightning protection” D. Müller-Hillebrand already criticized the use of radioactive lightning rods, and the heavy discussion at 12th ICLP, Portoroz, Yugoslavia (1973) led by another “giant of lightning research” C. Berger showed both the theoretical and practical problems. Recently several non-conventional lightning protection systems have appeared again both in the scientific and business world. The non-conventional lightning protection solutions are the Early Streamer Emission (ESE) rod and Dissipation Arrays (sometimes called Charge Transfer Systems). There was and even now there is pressure at the international level (scientific conferences, national and international standards, www.intlpa.org) to use these systems in many parts of the world.

The competitor of the conventional lightning protection systems (air termination system built of several Franklin rods positioned on the basis of theoretical considerations) is usually a single non-conventional protector (chosen and built on the idea of its improved protected area). The problem is that this rivalry was often based only on economic considerations instead of theoretical discussions and world wide validation of performance and application in practice for several decades.

The International Conference on Lightning Protection (Cagliari, 2010, www.iclp-certre.org) paid special attention to the non-conventional lightning protection systems. One of the invited lectures focused on this topic [2] and a special Session was also organized. As the speaker Vernon Cooray summarized recently, the experts have had difficult discussions on the theory and practical operation and the comparison of the efficiency of the conventional and non-conventional lightning protection methods. In the above mentioned invited paper both the scientific basis of these systems and their performance were reported following the authors own results and the scientific literature among other publications that of CIGRE WG 405 of SC C4.

To tell the truth several problems have appeared.
- The discussions turned away from scientific questions.
- Instead of basic physical phenomena often only the protected volume is the topic of the debate.
- Based upon the suggestion of the users of ESE the efficiency of one single ESE rod is compared with the air termination system built of several Franklin rods (because of economic reasons).

However the performance of the Franklin rods has been validated in a large number of studies conducted around the world for many decades, the non-conventional systems have been introduced into several lightning protection standards without testing them over a long period of time in the field to validate their performances.

5. Discussion
The original idea that a protected space exists around air termination systems has been disproved. Nowadays the world wide accepted opinion is that the protected effect of an air termination has to be treated as a probability problem. Instead of searching the protected volume, scientists want to define the attractive volume and based upon the probability approach the actual risk has to be compared with the accepted risk defined for the object [16].

The Probability Modulated Attractive Space theory (see Chapter 3.1.) and the designing method, namely the Method of Rolling Spheres (see Chapter 3.2.) is widely accepted and used nowadays all over the world. Even the international (IEC) and European standards (EN) adopted both of them (IEC CENELEC EN 62 305, Protection against Lightning, 2006) however the practical use of these new regulations are interfered with by several misunderstandings and even some failures [10, 11, 12, 13].

Preventive Lightning Protection uses forecasting in conjunction with preventive actions. This newly developed method is extremely fruitful in case of objects having changing level of risk in time and in space. Based upon soft computing methods PLP can be handled (planned, built up and operated) in several practical cases.

There are several laboratory experimental results showing that ESE is an interesting idea, but the principle does not work under natural field conditions. Till now there is no justification to prove that the performance of ESE rods is better than that of the Franklin rods. The results in the literature also
demonstrate that dissipation arrays cannot dissipate an approaching lightning flash either to the protected object or to the air terminal system. Contrary to the non-conventional devices, the performance of the Franklin rods has been validated for many decades. The use of protected volume leads to unlimited (uncontrolled) discussion with ESE. Problems can arise with both tall tower and flat roofs. Neither a single Franklin rod, nor a single ESE device can fulfill the requirements of air termination systems. Based upon the electro-geometrical concept and the probabilistic approach they both have to be used with well defined reduced attractive volume of the object to be protected.

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