Budapest University of Technology and Economics
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The Further Development of the Probability Modulated Attraction Space Theory

Lightning Protection of Constructions with Special Geometry, Especially in Renewable Energy Production

Ph.D. thesis book

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List of Abbreviations

DEGM .....**D**ynamic **E**lectro-**G**eometric **M**odel

EGM .....**E**lectro-**G**eometric **M**odel

EBN .....**E**quipotential **B**onding **N**etwork

HSPP .....**H**ousehold-**S**ized **P**ower **P**lant

LPL .....**L**ightning **P**rotection **L**evel

LPS .....**L**ightning **P**rotection **S**ystem

MM .....**M**esh **M**ethod

MTBF .....**M**ean **T**ime **B**etween Shielding **F**ailures

PAM .....**P**rotection **A**ngle **M**ethod

PMAS .....**P**robability-**M**odulated **A**ttraction **S**pace theory

PS .....**P**ower **S**ystem

PV .....**P**hoto**V**oltaic

RSM .....**R**olling **S**phere **M**ethod

SPD .....**S**urge **P**rotection **D**evice

SPS .....**S**ecunder **P**rotection **S**ystem

Chapter 1
Description and Objective of the Topic

Lightning and its harmful effects have occupied people since the beginning. While it was initially bound to different gods, scientific studies have searched the origins of this phenomenon. Following ancient Greek scientists' work, Otto von Guericke recognized in the 16th century that lightning and electrostatic sparks generated by friction machines were different forms of the same physical phenomenon, electric discharges. **[Horváth, 1974]** Benjamin Franklin invented a lightning protection device in 1750. **[Franklin, 1750]** A metal rod was placed on top of the building, grounded using a metal wire. Franklin explained the air termination rod's functionality because an electrical discharge at the top of the grounded metal rod neutralizes the charge in the cloud. Despite the misinterpretation, lightning rods have since been used successfully around the world. The air termination rod works by providing a safe point of impact for the lightning, and by ensuring that the extremely high lightning current is safely conducted to the ground. This type of lightning protection was applied first in Philadelphia in 1760. **[Horváth, 1974]**

Researchers working on lightning protection have been searching for centuries for the so-called protected volume assuming its existence nearby an air termination system. However, many practical lightning strikes have demonstrated that the protected volume cannot be defined in the vicinity of a lightning rod. Professor Tibor Horváth approached the problem from a different direction. Instead of a protected volume to define the attraction space of an object or a lightning protection system. He searched for the section of the space above the objects to be examined from which the lightning strikes would reach the object. Based on the *Electro-Geometric Model* (EGM), he aimed to determine the frequency of lightning strikes. **[Horváth, 1960, 1991, 1967, 2012b]** He developed the *Probability-Modulated Attraction Space* theory (PMAS) and the *Rolling Sphere Method* (RSM) to facilitate the editing and design of the placement of air-termination systems. The rolling sphere method **[Horváth, 1973]** was first published in 1973 by Professor Horváth. The rolling sphere method has been part of the Hungarian lightning protection standard since 1962. The rolling sphere method is now included in the literature and in the international standards around the world.

The *Dynamic Electro-Geometric Model* (DEGM) is used to determine the probability of a lightning strike on a given object (in the case of an installed primary lightning protection system, the air-termination system or the object to be protected). In more complex cases requiring higher computational accuracy, only PMAS, the *Probability-Modulated Attraction Space* theory provides a solution. **[Horváth, 1960, 1991; Horváth et al., 1978]**

The PMAS theory describes the relationship between a given arrangement and the attraction spaces (the attraction space of the object to be protected and the primary lightning protection system). The attraction space of object to be protecting is the set of those points where $0 \leq P \leq 0{,}5$. All this statement is valid with the addition that the extent of this space depends on the polarity. This fact has already been confirmed by a large number of observational data and has also been demonstrated experimentally **[Horváth, 2012a]**. Introducing the factor $\varepsilon = z/h$, where z is the vector pointing from the orientation point, the top of the rod to a given point in space; and h is the height of the object relative to the plane (**Figure 1-1**). In the case of positive-polarity lightning, $\varepsilon > 1$, and negative-polarity lightning $\varepsilon < 1$.

The basis of PMAS theory is the orientation point. The point where the head of the downward leader going down from the cloud is when it is decided where it is going to strike. The orientation distance is the distance between the orientation point and the point of strike. (This practically means the last jump of the downward leader with the jumps towards the ground.) Several correlations can be written between the orientation distance and the lightning current (the peak of the lightning current wave), but Eq. E-1 is the best approximation for the relationship. Usually, a more straightforward form is used, which is satisfactory for low objects. The relationship describes that in the case of lightning strikes of higher currents, it is decided further where they will strike.

From the orientation point, lightning strikes the object with a given probability. This probability value is called the impact factor β. In reality, the impact factor varies continuously from 0 to 1. According to the more straightforward approach, the boundary of attraction space is usually connected to the value $\beta = 0.5$. The consequence of the simplification is that the space inside the Attraction space is characterized by $\beta = 1$, and outside it by $\beta = 0$.

Eq. **E-2** describes the expected number of lightning strikes per year for the attraction space, while eq. **E-3** gives the value of dP/dr for the given point, the density function of the orientation distances.

$$\boldsymbol{I/I_m = (r/r_m)^p} \qquad \textbf{(E-1)}$$

$$\boldsymbol{N_{F_a} = N_G \int_{V_a} \frac{dP}{dr} dV} \qquad \textbf{(E-2)}$$

$$\boldsymbol{dP/dr = \frac{k\,p}{\sqrt{r\,\pi}}\; e^{-\frac{1}{2}k^2 p^2\, ln(r/r_m)^2}} \qquad \textbf{(E-3)}$$

where P the probability of the strike from *r* point;
k a parameter, which depends on the polarity of the lightning;
p usually a value between 1.2 and 2 (exponent of $I/I_m = (r/r_m)^p$);

r_m	the median value of orientation distance in meter;
r	the orientation distance in meter;
N_G	the lightning density in a given location, $\frac{lightning\ strikes}{km^2 \cdot year}$
N_{Fa}	the frequency of lightning strikes hitted the object, the number of lightning strikes for years;
I_m	the median value of lightning current in kA;
I	the lightning current in kA.

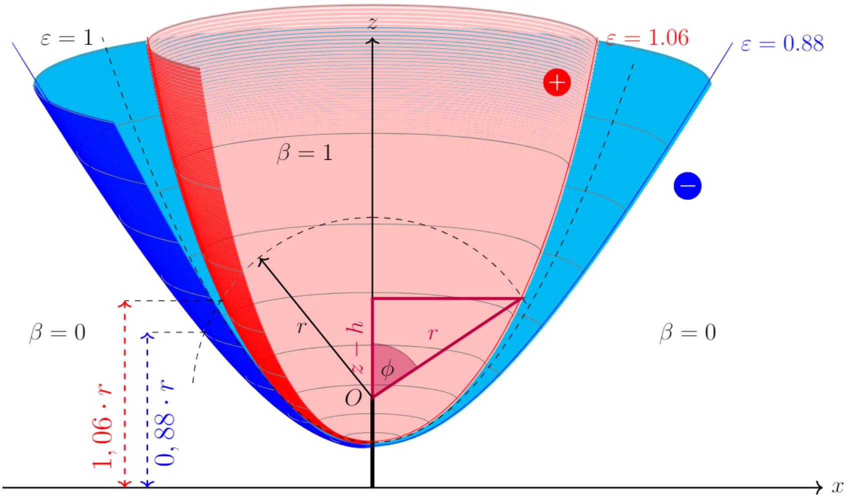

Figure 1-1 The Attraction space on the base of [Horváth, 1991]

During the tests and calculations, the goal was to prove that PMAS theory can be used to design wind turbine blades' lightning protection system. Another aim was to prove that from the point of view of lightning protection, it is not enough to separate the structure into a set of insulating and conducting components. It was important to make recommendations for PV power plants, which are becoming more and more widespread in Hungary as well. It has been shown which conditions need to be taken into account in the case of PV, high-power power plants during the lightning protection systems' construction.

Chapter 2
Antecedents

In the last decade, the share of renewable energy sources in Hungary's electricity production has been increasing. This is illustrated by the rapid spread of Household-Sized Power Plants (HSPP) on the one hand, and by the larger players, the large installed power plants in a series of installations. Since 2012, the construction of wind farms in Hungary has been indirectly prohibited, so their installed power has remained virtually unchanged since then. However, it is important to look at existing power plants as well. On the other hand, this dissertation's scientific results can be used elsewhere in the European and international community. This, in turn, could be an important opportunity to enhance the impact of domestic R&D. In this dissertation, not only the currently considered relevant topics are in focus but also all the issues that could gain more basis soon and as a problem in the international professional community (e.g. IEC, CIGRÉ).

The calculation methods and values are specified in the lightning protection standards, which can be used with high safety for low objects to be protected, cannot be used for high structures (e.g., wind turbines). **[Madsen et al., 2009]** For tall, complex geometry structures, neither the classical lightning protection design methods nor the DEGM can be applied. However, for more straightforward arrangements, the DEGM provides a good approximation. The PMAS **[Horváth, 1960]** theory gives more relevant and accurate results for complex works. PMAS theory takes into account – among other things –, the rate of the different polarity lightning and the physical differences. Demonstration of PMAS theory's benefits has already begun, but the process has not yet been completed in the literature.

With the spread of another type of renewable power plant, PV power plants, other issues arise. The hypothesis is that in PV power plants, primary lightning protection may be negligible in some cases under certain conditions. Due to the specific characteristics of these power plants (the special geometry and the effects of the surrounding built objects), in some cases, it is not necessary to install a primary lightning protection system as previously established for other structures.

Another question to be clarified in the Ph.D. dissertation is how the presence of structures of different materials should be taken into account in lightning protection risk calculation and design. This question is particularly interesting in windmills' design (the design of blades made of insulating material placed on high columns). Lightning protection problems often occur for parts made of an insulating material when designing and installing a lightning protection system for insulating roofs.

In addition to summarizing the scientific results, the dissertation aims to serve as a comprehensive, unifying, and clarifying work for the reader in the field of lightning protection, including the diverse use of both Hungarian and English literature.

Chapter 3
Research Methods

Several bad practices can be found, stemming from the incorrect application of different lightning protection design methods and from the misinterpretation of various theories. The most common methodological error is the false design applications of the mesh method (MM) where it is not taken into account that it is a tool for monitoring the systems designed. Still, in the opposite direction, this is not always applicable. Another common mistake is overvaluing or squeezing each theory. Most of the theories use simplifications for efficiency. Therefore they can only be applied under specific conditions. The sub-statements of theories must not be blurred with each other because each lives with not some simplification.

During the research, both quantitative and qualitative research was done as complements to each other.

In the qualitative research, the theories were reviewed that can be found and used more widely, which are now present in the international literature. For some of the theses, analytical and numerical calculations were done, for which the PMAS theory was used. In order to verify the authenticity of laboratory measurements, the validation price of the measurements was used for the control, numerical simulations.

Within the framework of the qualitative method, laboratory measurements were carried out to confirm the theories, or to allow them to be further developed the theory on the basis of the correlations resulting from the measurement results.

The results were published in national and international conferences and journals, performed and defended in professional forums.

Chapter 4
Theses

Thesis 1

The current international standards and the recommendations are contained in them only deal with the metal structural elements of wind turbine blades (they interpret that the lightning strike will only hit the air-termination). Still, practice shows that the windmill blades' insulating surfaces are often damaged by lightning strikes directly.

Contrary to researchers' general perception in the field of attraction space, it has been shown that it is not sufficient to consider only the metallic structural parts of a wind turbine blade when designing the lightning protection system for wind turbines.

It has been proven that the insulating materials used in wind turbine blades must also be taken into account when designing the blade structure and lightning protection. The electrical properties of the insulation materials used and their environmental changes must be examined in detail.

Own publications related to the thesis

Conference presentations

[Z. Tóth et al., 2016], **[Z. Tóth & Kiss, 2017c]**, **[Z. Tóth & Kiss, 2017a]**, **[Z. Tóth, Kiss, et al., 2017]**

Conference publications

[Z. Tóth & Kiss, 2017c], **[Z. Tóth & Kiss, 2017a]**, **[Z. Tóth, Kiss, et al., 2017]**

Journal papers

[Z. Tóth & Kiss, 2017b], **[Z. Tóth, Kiss, & Németh, 2019a]**

The conclusions were drawn based on previous measurements and their results **[Horváth, 1991; Z. Tóth, Kiss, Németh, et al., 2019]**, as well as the results of the experimental measurements which were published in **[Z. Tóth, Kiss, & Németh, 2019a; Z. Tóth & Kiss, 2017c]**. During the construction of a given air-termination system, the proportion of a given polarity lightning current is determinative. From there, it can be determined how densely necessary to place the air-termination receptors on the insulating blade to achieve an adequate level of protection. If the positive-polarity lightning currents' proportion is higher, the risk increases to reduce the air-termiantion system's effectiveness. Polarity dependence is not addressed in practice. This results the deviation of results in the lightning protection standards and practice in a given area. The experiments were performed by taking into account the polarity dependence for the following arrangements:

- stand-alone air termination rod (**Figure 4-1**) and
- wind turbine model (**Figure 4-2**).

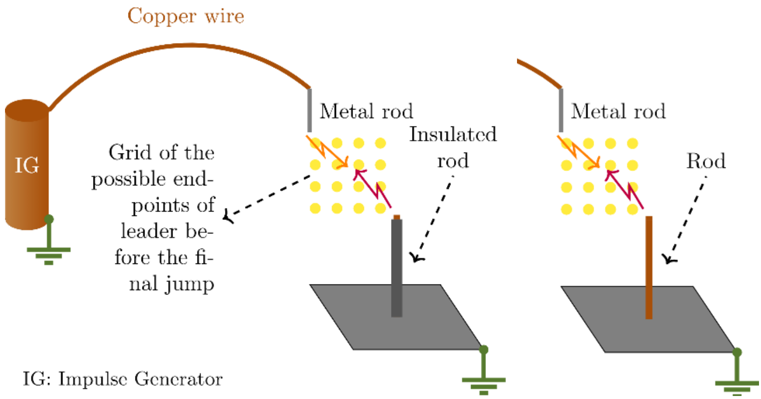

Figure 4-1 Schematic diagram of the arrangement for a single (left) insulated and (right) uninsulated air-termination rod [Z. Tóth et al., 2016; Z. Tóth, Kiss, & Németh, 2019a; Z. Tóth & Kiss, 2017b, 2017c]

In the experiments, some space-deformation effect of the insulating layer was expected. To determine the deviation between the two attraction spaces, a simplified wind turbine model (**Figure 4-2**) was applied in different blade positions.

The experiments were also performed on a single rod, which was used to determine the attraction space of a single-standing, high object in two cases: with and without an insulating layer. It was observed (**Figure 4-3, Figure 4-4**) that the value of attraction space along the rod was significantly reduced, and the attraction space of the ground was also distorted.

Taking into account previous measurements **[Birkl et al., 2018; Garolera et al., 2012; Madsen, 2017; Madsen et al., 2009]**, other measures were made for a wind turbine model. Two types of wind turbine models have been created for laboratory testing. The boundary of the attraction space differs significantly, taking into account the insulating material if only the geometry is taken into account from the point of view of lightning protection.

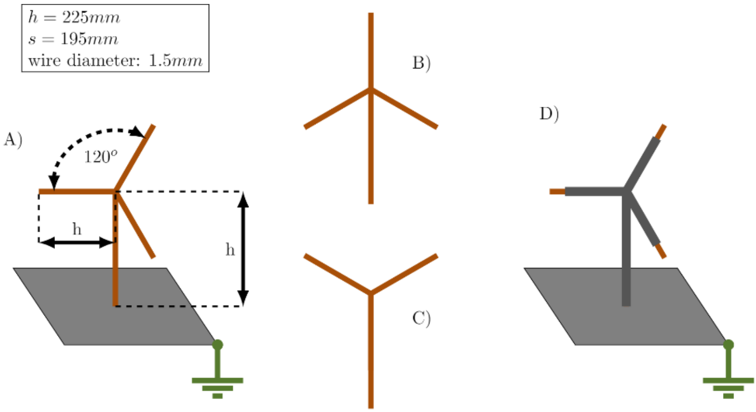

Figure 4-2 Schematic diagram of the arrangement for the wind turbine in different blade angle (A, B, C); case of the insulated arrangement(D) [Z. Tóth & Kiss, 2017a, 2017c]

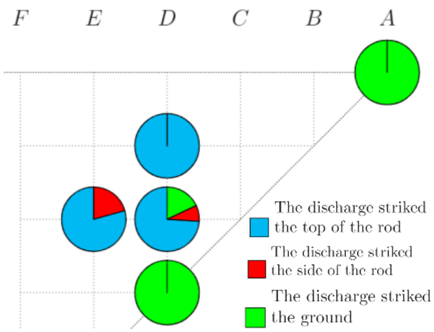

Figure 4-3 Frequencies of discharges from a given orientation point in the case of an insulating layer (positive polarity). [Z. Tóth et al., 2016; Z. Tóth, Kiss, & Németh, 2019a]

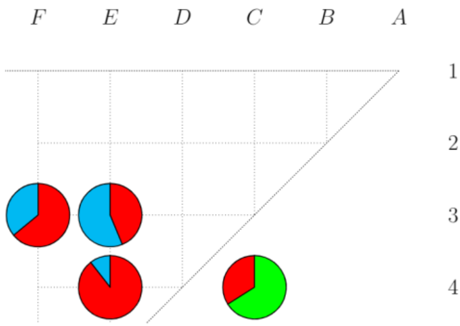

Figure 4-4 Frequencies of discharges from a given orientation point in the case of an insulating layer (negative polarity). [Z. Tóth et al., 2016; Z. Tóth, Kiss, & Németh, 2019a]

Observations **[Holboell et al., 2006; Madsen et al., 2006]** show that negative-polarity discharges reach the air-termination receptors at a greater number than other points on the blade, as opposed to the positive-polarity case. Because of this, a more detailed laboratory experiment was done for positive-polarity discharges. The high *dP/dr* parts of the attraction space belong to the end of the blade. The result was obtained similar to the results obtained during the laboratory observations with the theoretical calculations. The insulating layer reduces the attraction space.

The results obtained in **[Kiss et al., 2014]** show well why the most damage occurs near the blade tip: here, the probability is that the orientation point is in a given *dV* volume element that is closer to the blade. This result also confirms that a single receptor located at the blade's tip is not sufficient for large wind turbines. A multi-receptor arrangement was studied by Madsen et al. **[Garolera et al., 2012]** too.

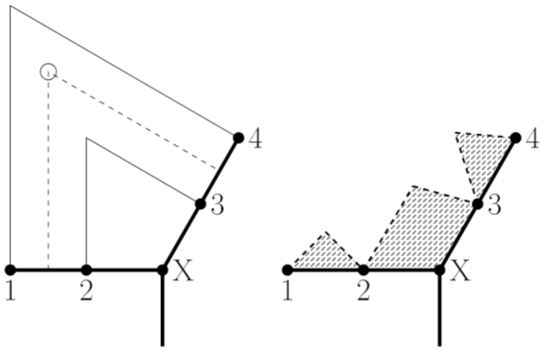

Figure 4-5 The borders of the attraction space of the wind turbine blades (left) do not take into account the insulating layer; or (right) taking into account the insulating layer. [Z. Tóth & Kiss, 2017a, 2017c]

If the model considered only conductive material, then the parts marked with solid lines in **Figure 4-5 (left)** will be the attraction space of each receptor, since the surrounding parts will also be conductive, so they will also have a similar part, too. If the blades are made from an insulating material, and each point (1, 2, 3, and 4) represents a receptor, so the attraction spaces are bounded by the part indicated by the dashed line separated by parts 1-2, 2-x, x-3 and 3-4. The point O indicates a point equidistant from the four points (1, 2, 3 and 4), but the nearest parts are parts of the blades made from insulating material.

Table 4-1 The result of the laboratory measurements for wind turbines with two receptors. [Z. Tóth et al., 2016; Z. Tóth, Kiss, & Németh, 2019a]

Measurement points	1		2		X		3		4	
Measurement 1	0	0	0	0	0	0	4	0	21	/25
Measurement 2	2	3	3	0	0	0	1	0	16	/25

Considering that the length of the receptors is *dx*, the lines become sections with width xx, but the integrated value of the *dP/dr* values still gives too low a result for the given volume. A better fit was obtained between the calculated and measured (**Table 4-1**) results after modifying the attraction space. In this case, the surface of attraction space of the insulated blades decreases, as shown on the right side of **Figure 4-5**.

Even when designing the blade structure, it is not enough to consider only the wind turbine blade's metallic structural parts. It is also necessary to test the insulating materials used for wind turbine blades (the parts made from an insulating material or covered with an insulating layer). This means that the application of PMAS for wind turbines allows the insulation layers to be taken into account already in the design phase.

Thesis 2

A new calculation method has been developed based on the probability-modulated attraction space theory to calculate the risk of lightning strikes for the peculiar photovoltaic power plants (large area but small height), which provides more accurate results than the existing, standardized, sometimes excessively-demanding methods. The protective effects of the objects of comparable height to photovoltaic tables in, or in the immediate vicinity of the photovoltaic power plant (safeguarding objects, fence, lighting, or camera tower) have to be taken into consideration, too.

Own publications related to the thesis

Conference presentations

[Z. Tóth, Kiss, et al., 2017], **[Z. Tóth, Kiss, et al., 2020]**

Conference publications

[Z. Tóth, Kiss, et al., 2017], **[Z. Tóth, Kiss, et al., 2020]**

Journal papers

[Z. Tóth et al., 2018], **[Zoltán Tóth et al., 2021]**

The part of PV power plants is growing significantly from year to year. This requires increased operational safety, too. This is the only way to ensure that, while the share of PV power plants in the electricity market grows, the electricity supply's security will also increase. One of the critical conditions for safe operation is the modern and economical light protection of photovoltaic power plants. In the case of PV power plants, in contrast to wind turbines, the classic lightning protection design methods can be applied. The aim of effective lightning protection is to avoid a drastic increase in costs while reducing expected damage. After all, the best of both technical and economic points of view do not prevent lightning protection but facilitate the rapid spread of PV power plants.

The international literature could meet several times in recent years, with the proposal that lightning protection is optional on the basis of economic criteria. **[Christodoulou et al., 2016; Hannig et al., 2014; Rousseau et al., 2004]** On this subject's own publications and book chapters (journal article) also appeared. **[Z. Tóth et al., 2018; Z. Tóth & Kiss, 2017b]**

The problem can be approached from several directions:

A) the likelihood of damage and its effects; **[Z. Tóth et al., 2018; Z. Tóth & Kiss, 2017b]**
B) whether the solution is compliant from a standardization point of view (if not, does the standard not need to be revised); **[Rousseau et al., 2012]**
C) secondary effects of lightning and the damage they cause must be analyzed. **[Charalambous et al., 2014; Salinas et al., 2018; Zaini et al., 2016]**

During the research work, the first two aspects were taken into account. As a first step, the expected risk was determined using the PMAS method.

PV power plants can be interpreted as a special arrangement compared to conventional buildings and other built objects. On the one hand, it is possible to talk

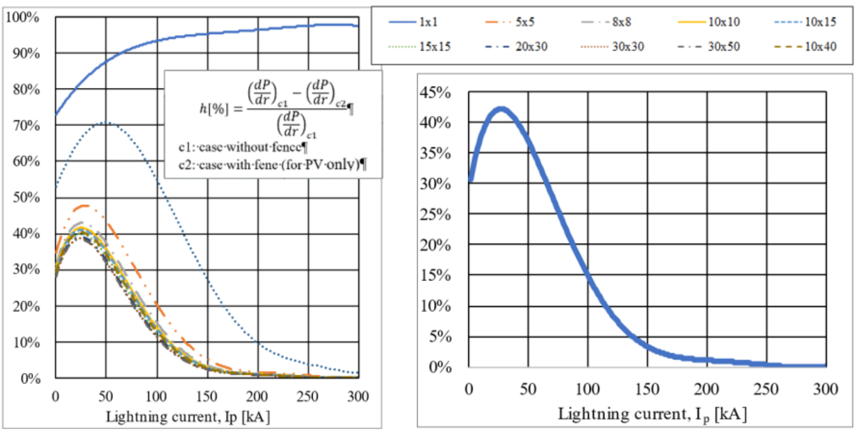

Figure 4-6 ***Left:*** **Difference in PMAS calculation results (reduction of PV panel impact) in % for PV parks of different sizes as a function of the occurrence of the lightning current [Zoltán Tóth et al., 2021];** ***Right:*** **Limit value of the results and differences of the PMAS calculation [Zoltán Tóth et al., 2021]**

about relatively low structures, and on the other hand, the floor area of the power plant can be extremely large. (The occupied floor space increases in proportion to the installed power.) The PV power plant arrangement is also special in that it is made up of repeated, similar units, and the edges of the power plant are most exposed to the increased risk of lightning strikes.

At present, both the installation and the periodic lightning protection inspections examine the lightning protection air-termination systems. They do not take into account each object with a height comparable to the PV tables in the power plant or its immediate vicinity. Calculations based on the PMAS theory have shown that the additional security elements (safeguarding objects, fence, lighting, or camera tower) should be considered as air-termination. In this way, the lightning protection level can be reduced for the entire PV power plant.

A trend can be readout by performing the PMAS calculation for specific PV systems with regular, repetitive elements. The current values in the standard are limit values in the case where they have a kind of limit, below/above which the partial value cannot be considered to be classified in the given class. The easiest way to link this to the frequency could be as follows:

$$\boldsymbol{f = {}^{1}/_{N_G \cdot A_{eq}} \left[\frac{year}{strike}\right] \geq 10^{C}} \qquad \textbf{(E-4)}$$

where *C* is a variable depending on the classification (LPL I: 5, LPL II: 4, LPL II-IV: 3).

In the following (**Figure 4-6, left**), change the block sizes as a function of the distribution of lightning currents, the number of lightning strikes were plotted for the PV park compared to the case without the security fence in proportion to the fence calculations, as a percentage. From the values obtained in this way, I state that in the case of larger PV parks, the rate of change in the case of smaller lightning currents (I_p < 50 kA) is between -30% and -40%, while in the case of I_p < 100 kA it is between -10% and -15%, for I_p < 150 kA it is between -5% and -8%.

The **right side of Figure 4-6** shows the theoretical limit of the previous calculations, which gives the shielding effect of all systems/objects that are not direct parts of the PV power plant but e.g., belong to the security objects.

It was proved by calculation that a general part for PV power plants could be used in practice, even when implanted in the standard, in accordance with the lightning protection levels determined by the special application of the PMAS method. The result of the calculations and case studies is that the lightning protection level for LPL III can be reduced by one class to LPL IV.

In some cases, primary lightning protection is not required within a given dimension range. In these cases, the PMAS calculation must be performed in all cases to determine the attraction space of the security objects, or if the size of the PV power plant is large enough to become necessary. In this case, the same procedure must be used like for air-termination rods.

Thesis 3

The current international standard gives a limitation for the height of the air-termination mesh in case the roofs of buildings are made from flammable material. In contrast, neither in the standard nor in the international literature is there a restriction on the air-termination mesh's height if the roof of the building is not made from flammable material.

It has been shown by laboratory measurements and modeling that the material of the roof cannot be neglected when performing the risk calculation during the design of the air-termination mesh, even if it is not a flammable (non-flammable) material.

It has been shown that the design of air-termination mesh according to RSM (Rolling Sphere Method) gives incorrect results for roofs made from insulating, non-flammable material. It has been established for insulating roofs and proved that air-termination mesh's risk calculation should be performed according to the Probability-Modulated Attraction Space theory instead of using the rolling sphere construction method.

Own publications related to the thesis

Conference presentations

[Z. Tóth, Kiss, & Németh, 2019a], **[Z. Tóth, Kiss, Németh, et al., 2019]**, **[Z. Tóth, Kiss, & Németh, 2019b]**, **[Z. Tóth, Kálecz, et al., 2019]**

Conference publications

[Z. Tóth, Kiss, Németh, et al., 2019]

Journal papers

[Z. Tóth, Kiss, & Németh, 2019a], **[Z. Tóth, Kiss, & Németh, 2019b]**, **[Z. Tóth, Kálecz, et al., 2019]**

In lightning protection, the Mesh Method (MM) has been prevalent mainly in flat roof structures. Previously, they started from the assumption that the grid protects the object to be protected by forming a Faraday-cage-like arrangement. Examining the grid using the Rolling Sphere Method (RSM), an interesting conclusion could be reached. The roof structure made from conductive material must be connected to the equipotential bonding (EPB) so that the roof will be an integral part of the lightning protection system. In the case of a roof structure made of insulating material, a different situation develops depending on whether the roof is made of flammable material or not. The previous Hungarian standard (MSZ 274) defined the height of the air-termination mesh depending on its material. In contrast, the international standard **[IEC, 2011]** introduced here, although it does not distinguish between highly flammable and non-flammable roofing material, but determines the height of the air-termination mesh depending on the cooling time of the molten metal.

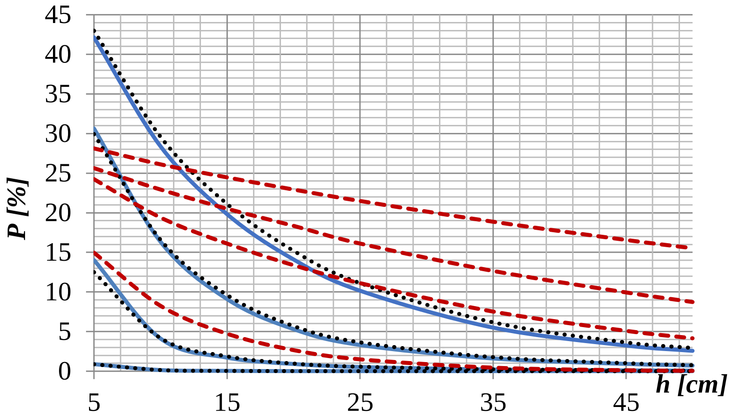

Figure 4-7 The results of calculations for a 40 m × 40 m mesh [Z. Tóth, Kálecz, et al., 2019; Z. Tóth, Kiss, Németh, et al., 2019]

The air-termination mesh could also be placed directly on the roof, as long as its material is non-flammable. The grid can also be placed on an insulated or uninsulated support structure. In these cases, the attraction space's cross-section would give the attraction space of a point-to-line arrangement. With this arrangement, the probability – that lightning strikes the roof –, may be higher in the middle of a given mesh. This means that the number of lightning strikes on the roof will be proportionally larger. However, experience does not show this. Air-termination mesh has worked well for the last century.

In the **Figure 4-7**, the continuous blue curve is based on the results of Kern et al. **[Kern et al., 2012]**; the red, dashed curves are calculated by Professor Horváth **[Horváth, 2012b]**. The values of the black, dotted curve are the result of our own calculation. The own results **[Z. Tóth, Kálecz, et al., 2019; Z. Tóth, Kiss, Németh, et al., 2019]** were compared with previous studies. The question in these calculations is when the *Dynamic Electro-Geometric Model* (DEGM) gives sufficient accuracy and when the *Probability-Modulated Attraction Space* (PMAS) theory should be used in order to keep the error to a minimum. In **Figure 4-7** there is a significant difference between the red and the other curves. There are three main reasons:

1. Professor Horváth **[Horváth, 2012b]** considered a different height of the building than Kern et al. **[Kern et al., 2012]** (10 m instead of 20 m).
2. I used a different density function **[Horváth, 2012b]** than the standard **[IEC, 2011]**.
3. The boundary of the attraction space is different **[Horváth, 2012b]** than according to **[Kern et al., 2012]**. This difference becomes significant in the case of a larger mesh because the overlap of the real distribution of *b* values (not in the case of simplified attraction spaces) cannot be neglected. A more detailed analysis of this can be found in **[Horváth, 1991]**.

To illustrate the above effect, a laboratory measurement was performed using an air-termination system that included four conductors on the sides of a square (see **Figure 4-8 right**) and another case, the same with four air-termination rods at the corner of the mesh (see **Figure 4-8 left**).

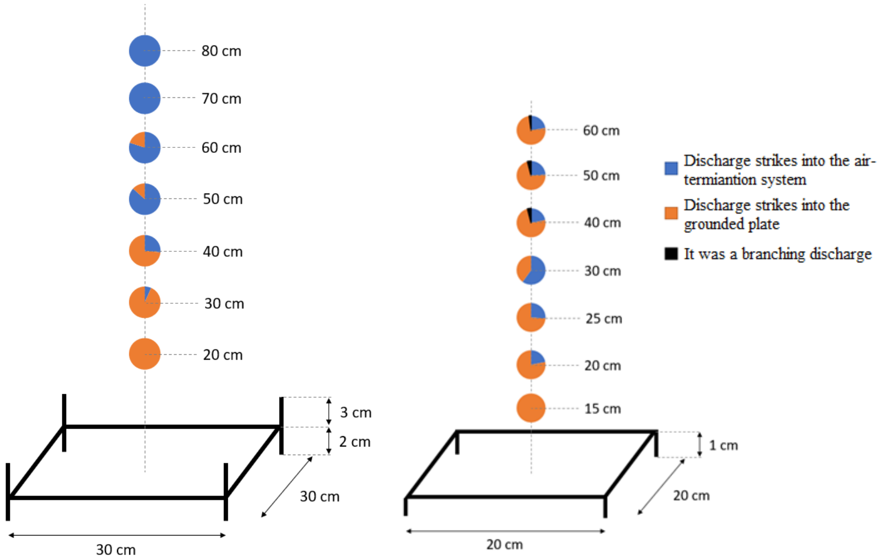

Figure 4-8 The results of the arrangements for the air-termination mesh [Z. Tóth, Kálecz, et al., 2020; Z. Tóth, Kiss, Németh, et al., 2019]

The number of expected discharges in different structures does not only depend on the geometric arrangement. In the design process, it is useful to base the lightning protection system's design on geometric data, but additional factors must be considered to determine efficiency. One of these factors is the material of the object to be protected.

In the case of a roof structure with a purely conductive material, laboratory experiments were performed. The performed model fitting makes it clear that the arrangement considered to be purely insulating and purely conductive is a misconception, which is thus significantly different from practical experience. If not a purely good conductor, the material of the roofs must always be taken into account by some geometric factor.

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