www.czasopisma.pan.pl PAN www.journals.pan.pl

BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 69(4), 2021, Article number: e137548
DOI: 10.24425/bpasts.2021.137548

POWER SYSTEMS AND POWER ELECTRONICS

Selected requirements for lightning protection in the light of actual standards and regulations on the example of an object to be protected

Anna DĄDA[1*], Paweł BŁAUT[1], and Piotr MILLER[2]

[1] AGH University of Science and Technology, Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering, al. Mickiewicza 30, 30-059 Krakow, Poland

[2] Lublin University of Technology, Faculty of Electrical Engineering and Computer Science, ul. Nadbystrzycka 38D, 20-618 Lublin, Poland

Abstract. Elements of the lightning protection system (LPS) often perform additional functions in the facility. Correct and economical design of these elements is possible with the fulfillment of specific requirements, close coordination and inter-branch cooperation. The article draws attention to important aspects of LPS design and highlights the ambiguities that may arise during this process. Firstly, the history of changes in national standardization in the field of lightning protection is approximated. Secondly, the individual components of external LPS are presented. Subsequently, the normative material requirements for earthing are compiled, depending on their function (for lightning protection and protection against electric shock in MV and LV installations). The last part of the paper is devoted to the comparison of the protective angle method and the rolling sphere method. The analysis was made on the example of a simple object for which LPS class I is required. It has been shown that despite the possibility of using both methods, they may result in different solutions. Depending on the choice of method, the difference in the arrangement of the air-termination system is indicated. Examples of generally available LPS solutions are also given, taking account of various materials and assembly technologies.

Key words: lightning protection system (LPS); 62305 standard; air-termination system; earth electrodes; protection of building objects.

1. INTRODUCTION

According to the currently binding Regulation [1], all buildings specified in the Polish Standard that applies to lightning protection of building objects [2] shall be equipped with a lightning protection system (LPS) and an artificial foundation earth electrode.

The main task of lightning protection is to intercept a lightning flash, then to discharge and dissipate the lightning current into the ground. A properly designed lightning protection installation reduces the risk to a tolerable level. The designer of this installation should cooperate with other discipline engineers. The cooperation enables the use of natural parts of the protected facility as elements of the lightning protection system. It also allows to avoid errors in the execution of the foundation earth electrode. This is particularly important, because it is not possible to interfere with this element once the foundation is set in concrete. Such an approach minimizes the costs and difficulties of implementing LPS, while increasing the final aesthetics and effectiveness of building protection [2, 3].

Extensive requirements placed on the elements of an external lightning protection system can lead to ambiguities and errors in the design and implementation of installations. For this reason, this article will attempt to identify solutions that guarantee the greatest possible reliability and effectiveness of lightning protection installations.

*e-mail: annadada0709@gmail.com

Manuscript submitted 2021-02-28, revised 2021-04-15, initially accepted for publication 2021-05-06, published in August 2021

2. HISTORY OF LIGHTNING PROTECTION SYSTEM REQUIREMENTS

2.1. How the standards on lightning protection have changed

One of the first documents that had regulated the measures of the lightning protection system was the PN-E-05003:1955 standard. It contained general rules for the construction and exploitation of lightning protection devices. This standard did not cover the protection of particularly endangered buildings (e.g. buildings at risk of explosion), power and telecommunications equipment or special equipment. Over the years, the requirements for lightning safety of installations and devices have increased. The installations and devices have become more complex, more expensive and also more sensitive to overvoltages. Knowledge about lightning flashes has continued to be constantly developed, allowing for preparation of standardization documents, which strive to meet growing expectations.

Thus, in the 1980s and early 1990s the standard from 1955 was replaced with a new four-part version. In addition to general requirements and basic protection, it also introduces special and tightened protection:

- PN-E-05003-01: 1986 – General requirements,
- PN-E-05003-02: 1986 – Basic protection,
- PN-E-05003-03: 1989 – Tightened protection,
- PN-E-05003-04: 1992 – Special protection.

In 2001 and 2002, a series of PN-IEC 61024 standards, which consisted of three parts: PN-IEC 61024-1, PN-IEC 61024-1-1 and PN-IEC 61024-1-2, appeared. The standard introduced new solutions, including four levels of protection that corresponded to the different lightning protection device efficiencies. The procedure for assessing the risk of damage had also changed. As a result, the necessity and required efficiency of lightning protection system in an object were stated. Interestingly, a series of 61024-1 standards replaced part 2 of PN-E-05003-02: 1986 standard only. The other three parts had coexisted with the 61024-1 series, until the introduction of the PN-EN 62305 series standards.

In 2001–2004, a series of PN-IEC 61312 standards dedicated to protection against electromagnetic pulse were introduced. These standards did not replace the previous ones, but were somehow a supplement to them. This state of affairs had lasted until the implementation of the currently applicable standards of the PN-EN 62305 series. These standards replaced all the previously mentioned standards. The PN-EN 62305 standards include four parts, which are dedicated to various aspects of lightning protection:

- PN-EN 62305-1:2011 – indicates general rules for protecting objects against lightning flashes,
- PN-EN 62305-2:2012 – is dedicated to risk management, enables the selection of protection measures ensuring that the risk is reduced to the required safe level,
- PN-EN 62305-3:2011 – comprehensively discusses the principles of design, implementation, checking and operation of a lightning protection system,
- PN-EN 62305-4:2011 – includes requirements for the protection of electrical and electronic systems.

Originally, the above standards were introduced in 2006 in the English version, while in 2008–2009 also in the Polish version. Compared to previous standards, significant changes were introduced in the approach to the lightning damages (risk) assessment and to sensitive structure equipment protection against surges.

The next step was to regulate the issue of material and construction requirements to ensure adequate reliability of the lightning protection system. In 2011–2012, a 7-part PN-EN 62561 standard was introduced, concerning the subject of lightning protection elements. It was updated in 2017–2018. It addresses issues such as the general requirements for connecting elements and the selection of materials for elements of the lightning protection installation. It also contains the requirements for current surge meters, substances improving the quality of earthing, control chambers and spark gaps.

2.2. How the standards dedicated to requirements of materials in lightning protection have changed

The currently applicable PN-EN 62561 standards have replaced earlier PN-EN 50164 standards from 2002–2009. Both standards raise the same subject. Part 2 covers the requirements for the materials of which the lightning protection system shall be made.

The most important changes regarding the requirements for the air-termination system, down-conductor system and grounding conductors include:

- introducing new materials such as the copper-coated aluminum alloy and copper-plated steel,
- reducing cross-section and diameter (from 200 mm^2 and Ø16 mm to 176 mm^2 and Ø15 mm) for materials such as the copper rod, galvanized copper rod, aluminum alloy rod, galvanized steel rod, stainless steel rod,
- meeting grounding requirements in addition to the requirements for grounding conductors if the grounding conductor is partially placed in the ground.

Changes regarding the requirements for earth electrodes are:

- increasing the coating thickness for copper-bonded steel for all types of grounding to 250 μm,
- changing the requirements for embedding in the concrete earth electrodes such as steel tape, galvanized steel cable and galvanized steel tape,
- reducing the required dimensions of a copper or galvanized copper plate (from 2 mm to 1.5 mm).

It should be noted that at the same time, the requirements for materials used in lightning protection appeared in the PN-HD 60364-5-54:2011 standard, next to the requirements for materials used in electric shock protection. In addition, other earth electrodes were added for materials such as copper, copper galvanized steel and galvanized steel. There is also the item called "steel embedded in concrete (bare, galvanized or stainless)". The tinned copper and galvanized copper were removed. Greater emphasis was placed on the thickness of the coatings. In the PN-EN IEC 62561-2 and PN-HD 60364-5-54 standards, changes in material requirements mainly consisted in detailing of existing ones, or adding new requirements for materials. It resulted from many years of experience and a disposition to unify the regulations. In most cases, these changes are minor and significant corrections occur sporadically.

3. ELEMENTS OF LIGHTNING PROTECTION SYSTEM

Complete protection against lightning within structures consists of a lightning protection system (LPS) and additional surge protection measures (SPM) that reduce the lightning electromagnetic pulse (LEMP) [4]. Due to the limited volume, this part of the paper presents the most important elements of an external LPS lightning protection system.

3.1. Earth electrode – functions and most important aspects

The earth electrode of each object may fulfill three basic functions: lightning, protective and functional. Therefore, many aspects should be taken into account when designing the earthing system and selecting its materials. These aspects include: protection against lightning flash, protection against short-circuit currents, protection against electric shock, equipotential bonding and reliable operation of the electrical installation [5, 6]. It shall be remembered that protective functions are always a priority [7].

The PN-EN 62305-3 standard specifies two types of earth electrodes [2, 6]:

- the A type system is installed outside the building in the form of vertical or horizontal earth electrodes which are connected to the down conductors. It is also made in the form of foundation earth electrodes, which do not form a closed loop. This type of system shall consist of at least two earth electrodes,
- the B type system is constructed as a ring earth electrode or foundation earth electrode that forms a closed loop.

Important factors to be considered when designing the earth electrode are [2, 6, 8–11]:

- soil resistivity and the impact of weather conditions on its change,
- type of foundation (the possibility of providing of ground contact with the earth electrode, and thus the possibility of effective discharge of lightning current to the ground),
- external lightning protection system,
- other systems (e.g. IT system, medium voltage switchgears, utilities connected to the facility with pipelines such as water, gas, sewage system).

When designing the earth-termination system, the phenomenon of resistive coupling should be taken into account. This phenomenon occurs when the designed earth electrode is in the potential hopper area of another neighboring earth electrode or auxiliary earth electrode. As the distance between the earth electrodes increases, the coupling resistance decreases. The flow of current through one of the earth electrodes induces the electric potential on the neighboring earth electrode, posing a threat to people and devices in the object protected by the other earth electrode [12].

The touch and step voltages are other important aspects. They occur during the discharge of the lightning current into the ground through the down-conductor and earth-termination systems. In order to minimize the value of those voltages, a system containing at least 10 lead wires can be used (clause 8.1, part No. 3 of [2]). By providing multiple flow paths, the current is significantly reduced, thereby lowering the induction voltage value. In order to minimize touch and step voltage, it is also possible to provide transition resistance within a radius of 3 m from the down-conductor system at a level of ≥ 100 kΩ (clause 8.1, part No. 3 of [2]).

If the above conditions cannot be met, other solutions should be applied. The threat from step voltage can be minimized by use of a dense metal grille with mesh sizes 0.25 m $\times$ 0.25 m, buried at a depth of not more than 0.25 m [7]. It can also be obtained by making additional ring earth electrodes around the foundation earth electrode. The depth of burying the ring earth electrode should increase with increasing distance from the protected object. The depth should increase by 0.5 m for every 3 m of distance from the object [7]. Touch voltage threat can be minimized by the insulated discharge ducts, barriers, warning signs or the earthing control system [2, 7].

3.1.1. Foundation earth electrode

The foundation earth electrode is a metal closed ring embedded in the concrete foundation along the outer edge of the building. If the natural elements of the building such as concrete's reinforcement meet the minimum requirements, they should be used for this purpose first [2]. The foundation earth electrode shall be connected to the foundation reinforcement at intervals of not more than 2 meters. These connections shall be carried out in a way that guarantees a reliable electrical connection. The metal ring shall be surrounded by a layer of at least 5-cm-thick concrete. Particular attention should be paid to the connections between the foundation earth electrode and foundation reinforcement. Connections can be made by means of clamping, welding or screwing.

The dimensions of the foundation earth electrode mesh should be adapted to the size of the protected object, not exceeding the following values [3, 7, 13]:

- 20 m $\times$ 20 m for an object without an external lightning protection system,
- 10 m $\times$ 10 m for an object with an external lightning protection system,
- 5 m $\times$ 5 m for objects with particular restrictions and objects with particularly sensitive electronic devices.

Smaller mesh sizes and location of the foundation earth nodes in the places where the down-conductors are attached ensure better potential equalization in the building [3, 14].

The advantage of the foundation earth electrode over the ring earth electrode made outside the contour of the protected object is the significantly lower impact of weather conditions on earth electrode resistance [3].

3.1.2. Ring earth electrode

It may be necessary to build a ring earth electrode instead of, or in addition to, the foundation earth electrode. Such a solution is common for buildings settled below the lowest groundwater level. In this case, the building is provided with thermal insulation, which significantly reduces the groundwater impact. Unfortunately, thermal insulation causes a significant increase in transient ground resistance, "isolating" the earth electrode from the ground. This makes it difficult to discharge lightning currents to the ground. Consequently, the required grounding resistance is not met and the foundation earth electrode shall not play its role in lightning protection. In the event of a lightning flash, the lightning current would flow from the air-termination system to the foundation earth electrode and then to the ground, damaging the building's thermal insulation. Damaged insulation will not meet the required insulation parameters. This would also negatively affect the condition of the building's foundations. Over time, it could even cause a threat of serious damage to the building. The solution to this problem is the use of the ring earth electrode.

The ring earth electrode is made as a metal closed ring embedded in the ground. It may be installed outside the structure of the building. It may also be installed under the foundation in the ground or in a blind layer along the outer edge of the building. The dimensions of the ring earth electrode mesh depend on the dimensions of the structure. The smaller the mesh, the more effective the equipotentialization. However, the compaction of the mesh entails an increase in costs. A compromise must therefore be reached between these aspects. Clause 5.4.3, part 3 [2] recommends to install a ring earth electrode at a distance of 1 m from the external walls of the building at a depth greater than or equal to 0.5 m. In addition, attention to the roofs that extends beyond the building's outline should be paid. A roof that extends far beyond the outer walls of the building can affect the moisture of the earth where the ring earth electrode is located.

In objects with thermal insulation, a ring earth electrode does not fulfill the potential equalization function. Therefore, in addition to the ring earth electrode, the foundation earth electrode with the potential equalization function should be installed. Such a procedure will reduce the risk of electric shock [3, 7, 13].

3.2. Down-conductor system

The aim of the down-conductor system is to safely discharge the lightning current from the air-termination system to the earth-termination system. It shall be performed without endangering the protected object or people who are staying in it. The down-conductor system shall be designed in such a way that the path from the air-termination to the earth-termination system is as short as possible. There must be at least several paths for the lightning current flow. It should also be taken into account whether the lightning protection system is separated or not.

On the basis of clause 5.3.3, part 3 [2], the down conductors shall be installed at intervals depending on the lightning protection level (LPL I and II: 10 m, LPL III: 15 m, LPL IV: 20 m). If possible, down conductors should be an extension of the air-termination system. If the natural elements of the building meet the minimum requirements for down conductors, they should be used for this purpose first. Such natural elements are summarized in 5.3.5 in the third part of the standard [2].

3.3. Air-termination system

The purpose of the air-termination system is to intercept the lightning flash and discharge the lightning current to the down-conductor system. There are horizontal and vertical air-termination systems. They can be performed as: suspended wires, rods or wires in the ring system. The air-termination system can be placed on or outside of the object. It should protect not only the object itself, but also the devices located e.g. on its roof. Part 3 of the standard [2] presents three methods used for assessing the correctness of arrangement of the air-termination system:

- the rolling sphere method – applicable to each case,
- the mesh method – suitable for flat surfaces,
- the protection angle method – for buildings with simple shapes (the limitation of applicability of the protective angle method is the maximum height of the air termination, depending on the LPS class).

The required values of parameters appropriate for each method depend on the lightning protection level. These values are presented in Table 2 and Fig. 1 (clause 5.2.2, part 3) [2].

For objects lower than 60 m, the probability of side discharge is negligible, which is why the standard [2] does not require protection against side discharge in such buildings. In the case of objects taller than 60 m, the air terminations shall be placed on the side walls, in the upper part of the building (clause 5.2.3.1 and 5.2.3.2, part 3) [2].

When designing air terminations on the roofs, which are made of flammable materials, the building's ignition potential must be taken into account. Air terminations should not be in direct contact with the roof. A parallel distance of 0.15 m (thatched roof) or 0.1 m (other flammable materials) from the roof surface should be used (clause 5.2.4, part 3) [2].

To avoid spark jumps, appropriate spaces so-called separation distances, must be ensured. The air-termination system shall be arranged in such a way that all elements of the protected device are covered by the designated protected area. The separation distances shall be calculated according to the formulas in section 6.3. part 3 of the standard [2].

Natural building elements can be used as an air-termination system if they meet the minimum requirements for air terminations [2]. These are elements whose damage is acceptable, e.g. balustrades, decorations, metal tanks, metal layers of roofing, pipes, metal elements of the roof structure.

4. REQUIREMENTS FOR LPS MATERIALS

The selection of materials for the lightning protection system elements shall be carried out according to the strictly specified guidelines, described in applicable standards. The PN-EN 62561 series is dedicated to the elements of LPS and material selection. Tables 1 and 2 of part 2, contain the requirements for the materials of which the air-termination, down-conductor and ground-conductor systems shall be made. It should be kept in mind that in addition to the lightning protection, the earth electrodes usually have other functions. Thus, the selection of materials can cause many difficulties. The earth electrode shall meet the requirements of at least three standards: PN-HD 60364-5-54 (earthing arrangements of low-voltage installations), PN-EN 62305 / PN-EN IEC 62561 (lightning protection) and additionally e.g. PN-EN 50522 (when i.e. an MV switchgear and/or a transformer station is located inside the building).

Table 1 below compares the requirements for earth electrode materials according to four standards. Dimensions in brackets refer to electric shock protection, while dimensions without brackets provide both lightning and electric shock protection.

Analyzing table 1, it can be seen that the majority of requirements for earth electrode materials are consistent. However, there are also differences. When designing an earth electrode that performs many different functions, it is safest to assume the highest values for the selected material and shape (Table 1).

The undoubted limitation during the selection of materials is the electrochemical corrosion. To ensure long-term efficiency of the LPS, materials between which the electrochemical potential will be low enough should be used. The guidelines on corrosion protection are contained in [2] and [15] standards. It is not recommended to use galvanic connections especially between galvanized steel and copper (or copper steel) as well as galvanized steel and galvanized steel in concrete. For this connections, the potential difference can be from 0.5 V up to 1 V. This phenomenon can be prevented by the use of isolating spark gaps.

When choosing materials, attention should also be paid to the environmental impact. The conditions of using the materials are included in Table 5 of part 3 [2].

Table 1
Comparison of requirements for earth electrodes' materials according to PN-EN 62305-3:2011, PN-EN IEC 62561-2:2018 (red), PN-EN 50522:2011 (green) and PN-HD 60364-5-54:2011 (blue)

Material/configuration		Minimum cross sectionalarea [mm²]	Recommended dimensions [mm]	Coating/sheath [µm] Single values [µm]	Coating/sheath [µm] Average values [µm]
Copper, tin plated copper / bare copper / copper	Stranded	50 / 25 / (25) 50	single wire diameter: 1.7 / 1.8 / 1.7	1	
	Solid round (earth conductor)	50 / 25 / (25) 50	diameter: 8	1	
	Solid tape or strip	50 / 50 / 50	thickness: 2 / 2 / 2	1	
	Solid round (earth rod)	176 / (12) 15	diameter: 15	1	
	Pipe	110	wall thickness: 2 / 2 / 2 diameter: 20 / 20 / 20	1	
	Solid plate	2,500 cm²	thickness: 1.5 / (1.5) 2 area: 500 × 500	1	
	Lattice plate	3,600 cm²	area: 600 × 600 section for tape: 25 × 2 diameter for round conductor: 8 thickness: 2 mm	1	
Tinned copper	Stranded cable	25	diameter: 1.8	1	5
Galvanized copper	Strip	50	thickness: 2	20	40
Steel hot-dip galvanized	Solid round (earth conductor)	78	diameter: 10 / 10 / 10		50
				45	
	Solid round (earth rod)	150	diameter: 14 / 16 / 16	63	70
				45	
	Pipe	140	diameter: 25 / 25 / 25 wall thickness: 2 / 2 / 2	47	55
				45	
	Solid tape or strip	90 / 90 / 90	thickness: 3 / 3 / 3	63	70
				63	
	Solid plate	2500 cm² / 90	thickness: 3 / 3 area: 500 × 500	63	
	Lattice plate	3600 cm² / 90	area: 600 × 600 section for tape: 30 × 3 diameter for round conductor: 10 thickness: 3	63	
	Stranded (embedded in concrete)	70			
	Profile / profile / cross profile	290 / 90 / (290)	thickness: 3 / 3 / 3	63	70
Bare steel	Stranded	70	single wire diameter: 1.7		
	Solid round (earth conductor)	78	diameter: 10		
	Solid tape	75	thickness: 3		
Steel with extruded copper sheath	Round bar (earth rod)		diameter: 15	2000	
Steel with electrolytic copper sheath	Round bar (earth rod)		diameter: 14.2	90	100
Copper coated steel	Solid round (earth rod)	150	diameter: 14 / (15)	250 / 2000	
	Solid round (earth conductor)	50	diameter: 8	250	
	Solid round (earth conductor)	78	diameter: 10	250	
	Solid tape	90	thickness: 3	250	
Steel with electrodeposited copper coating	Solid round (earth rod)		diameter: 14	250	
	Solid round (earth conductor)		diameter: (8)	70	
	Strip	90	thickness: 3	70	
Stainless steel	Pipe		wall thickness: 2 diameter: 25		
	Solid round (earth conductor)	78	diameter: 10 / 10		
	Solid round (earth rod)	176	diameter: 15 / 16		
	Solid tape or strip	100 / 90	thickness: 2 / 3		
Steel embedded in concrete (bare, hot galvanized or stainless)	Round wire		diameter: 10		
	Solid tape or strip	75	thickness: 3		

5. LPS OF A SAMPLE OBJECT

A simple shape object was considered. Therefore, it is possible to use both the rolling-sphere method and the protective-angle method when arranging the air-termination system. The purpose of the analysis is to show the importance of method choice on the example of class I LPS. Exemplary solutions will also be discussed. The considered object is the space which determines the maximum dimensions of the damaged vehicle transporting hazardous materials. The vehicle in this space is a physical object which requires lightning protection. The dimensions of the considered object are: $20 \times 5 \times 4.5$ m (length, width, height).

According to Table 2 [2], for class I LPS the radius of the rolling sphere is $R = 20$ m. Isolated LPS was used due to the specificity of the object. A set of 4 vertical air terminations (Fig. 1) connected together with a ring earth electrode was adopted. The height of the terminations, determined on the basis of formula E.2 [2], is 12 m. As shown in Fig. 1, the rolling sphere does not touch the protected object in any considered space, so the object is fully protected.

5.1. Comparison between rolling sphere and protection angle methods

For comparison, protection by the same air-termination system was considered, but using the protective angle method. According to Fig. 1 [2], the α protection angle of 7.5 m high termination (regarding the top of the object) is 52° for class I LPS. The protected area at a height of 4.5 m does not cover the entire object, so protection is not provided (Fig. 1). Increasing the height of the terminations slightly improves the protection, but still does not provide it fully. This is because as the height of the termination increases, the angle of protection decreases significantly. Excluding the possibility of moving the air terminations closer to the protected object (e.g. due to restrictions resulting from the land development plan), the expected effect would be provided by:

- using an additional pair of air terminations in the middle of the longer sides while reducing the height of all of the terminations to 11 m,
- using horizontal air termination between the vertical ones on both long sides of the rectangle delimited by the terminations while reducing the height of all of the terminations to 11 m.

In both cases, reducing the height of vertical terminations does not compensate for the additional costs associated with the use of additional vertical or horizontal terminations. In the second case, vertical terminations shall have the strength to carry additional loads resulting from the suspension of horizontal terminations.

The analysis shows how important the choice of the method is. Unfortunately, the area of application of each method is not clearly and precisely defined in the standard, which leaves a certain margin of latitude and freedom of interpretation. According to the main part of standard PN-EN 62305-3 (clause 5.2.2), a rolling sphere method is appropriate in each case. Whereas the protection angle method is suitable for buildings (objects) of simple shapes. The height of air termination is restriction only for this method. It cannot be higher than the radius of the rolling sphere for the selected protection level. But the rolling sphere method is simultaneously indicated as appropriate for objects of complex shape in clause E.5.2.2 of the informative Appendix E. This is a significant difference from the main part of the standard and may affect the choice of method. As a consequence, it may lead to more stringent solutions being applied.

Both methods are suitable for the object being considered. Therefore, it is expected that they will give similar effects.

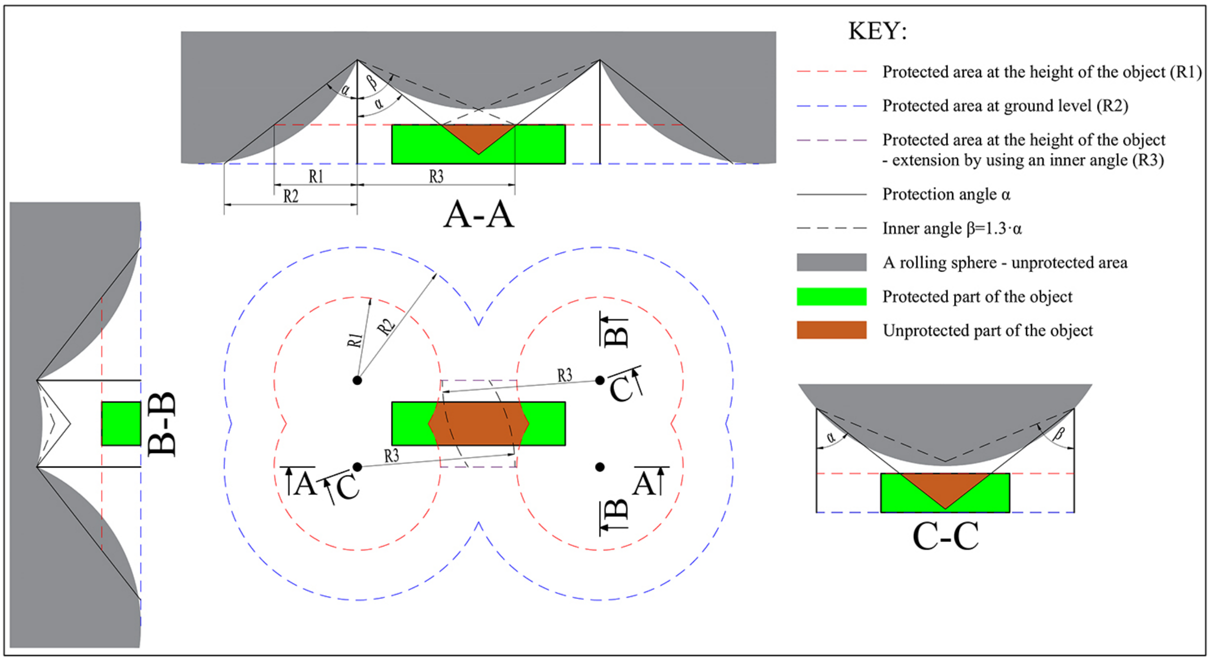

Fig. 1. Application of the protective angle and rolling ball methods for the object being considered

Meanwhile, significantly different results were obtained. To avoid such ambiguities, perhaps one of the methods should:

- not be used for a given type of object,
- be modified, so that the differences are not so significant.

In the first proposal, the application of the method could be conditioned by the complexity of the air-termination system, not by the complexity of the object. The area of application of the method could depend on the number of terminations, e.g. for a system of 3 and more terminations, the rolling ball method should be preferred.

Referring to the modification of one of the methods, it should be noted that in the standards of the PN-E-05003 series, the protective angle method (which was the only method at that time) distinguished between two protection angles: external α and internal β – between two neighboring terminals. The internal angle took into account the mutual influence of neighboring terminals on the protected area. Depending on the degree of protection, the β angle was larger than the external one by 1/3 or 1/2 (30° and 45° or 45° and 60°). Both angles did not depend on the height of the air terminals. The internal angle has been removed from the standards of the PN-IEC 61024 series. The lack of consideration of the mutual influence of neighboring terminals in the protection angle method, while making the angle of protection dependent on the height of the terminal, constitutes a significant tightening of LPS requirements.

In some cases, such a tightening of protection conditions deviates significantly from the requirements as compared to the rolling sphere method. These requirements of the rolling sphere method seem to be reasonable. When using the internal angle, the results for both methods are also very similar.

5.2. LPS support structures

There are at least several possible solutions of free standing air-termination systems available in the market. A common system solution is a lightning mast made of hot-dip-galvanized-steel, mounted on a prefabricated foundation [16]. The mast's construction serves both as a vertical air termination and a down conductor. This ensures a simple structure (no additional elements) enabling quick assembly, and also does not require many servicing activities, e.g. during periodic controls and inspections of the LPS.

Another solution is a composite pole with a lightning protection system, mounted on a foundation or dug into the ground [17]. This solution is characterized by a lightweight and easy-to-assemble structure with very low operating costs (minimum servicing) and long-term durability (resistance to corrosion and external environmental factors). It also provides a high level of safety, which may be important in public areas. The down conductor is located inside the pole and is surrounded by a non-conductive material of the pole. It protects the down conductor from external environmental factors.

In addition to the comprehensive solutions, other options are also available. A reinforced concrete pole or spun pole can be used, for instance, as a supporting structure for vertical air termination. On the top of such a pole a lightning rod is attached. The lightning current is brought to the earth electrode via a down conductor attached to the pole, e.g. by means of clamps and holders. Another option is to use lighting poles for lightning protection purposes. This can be done by using an adapter with the lightning rod attached to the top of the pole. When considering the purchase costs, these solutions are much cheaper than comprehensive ones. However, the assembly is definitely more time-consuming and requires many fixing points and connections. Inspection and operation are also more expensive.

5.3. LPS materials

An important element of LPS design is the proper selection of materials and their dimensions. When choosing the cross-section, the minimum required values of materials should be considered (Table 1). The maximum value of the expected lightning current and possible loss of the material due to increased corrosion over the expected lifetime should also be considered.

Relating these restrictions to the considered object:

- The use of steel lightning masts somehow imposes the necessity to construct an earth electrode made of galvanized steel (for mild soils) or much more expensive stainless steel. It significantly reduces the durability of this solution in soils with high chloride content. This impact can be leveled by using larger material's cross-sections;
- The use of composite masts and reinforced concrete/spun poles has no such restrictions. Depending on the needs arising from environmental conditions, any materials can be used. In an environment with a high chloride content, it can be copper or copper-plated steel. The composite masts additionally protect the down conductor, increasing its durability.

Depending on the existing conditions and established criteria, solutions may differ. It is possible to choose a solution cheaper in construction, but requiring more attention and maintenance during operation. It is also possible to choose a more expensive but also a more durable one. However, it should be remembered that the price criterion may not be the only one. A more expensive solution does not always have to be more effective or durable.

6. SUMMARY AND CONCLUSIONS

The lightning protection standards [2] are cited in the currently binding Regulation [1], which makes them mandatory to be used. Recommendations for the design and implementation of lightning protection have changed over the years, beginning with the 1950s. The direction of changes reflected in the standards is legitimated. Many issues have been systematized and ordered. On the other hand, providing protection requires much more attention.

The correct implementation of LPS requires comprehensive analysis. Elements of LPS can simultaneously perform other functions. Therefore, they should meet the requirements of several standards at the same time. For this reason, inter-branch cooperation is important at every stage of the project. Such cooperation enables cost reduction and eliminates potential errors and shortcomings. This is particularly important in the case of the foundation earth electrode, where after setting the concrete no corrections are possible.

To ensure proper installation lifespan, special attention should be paid to the selection of materials. Elements used for lightning protection should meet the requirements of the standard [2]. However, if these elements are also used for other purposes, they should also meet other requirements. Table 1 of this paper provides a comprehensive set of requirements for earth electrode materials. It contains requirements resulting not only from lightning protection standards [2], but also from overvoltage and electric shock protection regulations [9, 15].

Despite many advantages, some inaccuracies can be noticed in the standard [2]. As the analysis shows, for some cases the protection angle method can lead to a completely different solution than the rolling sphere method. This is despite the fact that the standard presents both methods as appropriate for the object being discussed. The protective angle method shows that lower but more densely spaced air terminations are definitely more effective. The height of the air termination has a relatively small impact on the protected area, especially for higher ones. On the other hand, the rolling sphere method shows that increasing the height of the air terminations can significantly increase the protected area. This allows for the use of fewer but higher air terminations. Even if the designer is guided by their experience and common sense, it is unlikely to avoid misunderstandings resulting from different interpretations.

Also excessive detailing of some issues can render implementation difficult, e.g. in the case of the risk assessment procedure. The algorithm includes at least several dozen of data. Except for objective data (such as dimensions in existing facility installations), there are also data depending on the subjective LPS designer assessment. A large amount of data and the potential for individual assessment can lead to incorrect risk assessment and, consequently, to choosing sub-optimal solutions.

REFERENCES

[1] Ministry of Investment and Development. "Regulation of Minister of Infrastructure of 12 April 2002 regarding technical conditions that shall be met by buildings and their location," Consolidated text JoL 2019 item 1065, as amended, Apr. 8, 2019.

[2] Technical Committee No. 55 (PKN/KT 55). "Protection against lightning," Series of standards PN-EN 62305 – Parts 1–4, 2011/2012.

[3] E. Musiał, "Foundation and ring earth electrode," *SEP INPE*, vol. 143, pp. 3–33, 2011.

[4] K. Aniserowicz, "Analytical calculations of surges caused by direct lightning strike to underground intrusion detection system," *Bull. Polish Acad. Sci. Tech. Sci*., vol. 67, no. 2, pp. 263–269, 2019, doi: 10.24425/bpas.2019.128118.

[5] M. Zielenkiewicz, T. Maksimowicz, and R. Marciniak, "Grounding installations – standards recommendations," *SEP INPE*, vol. 184–185, pp. 67–87, 2015.

[6] CBM Technology. "Earth electrodes." [Online]. Available: https://cbm-technology.com.pl/wp-content/uploads/2021/05/CBM-KATALOG.pdf [Accessed: 22. May. 2020].

[7] OBO Bettermann. "Earthing systems." [Online]. Available: https://obo.pl/media/Leitfaden_Erdungs-Systeme_pl.pdf [Accessed: 22. May. 2020].

[8] Technical Committee No. 173 (PKN/KT 173). "Telecommunications bonding networks for buildings and other structures," Standard PN-EN 50310, Sep. 27, 2016.

[9] Technical Committee No. 73 (PKN/KT 73). "Earthing of power installations exceeding 1 kV a.c.," Standard PN-EN 50522, Apr. 29, 2011.

[10] Working Committee NA 005-09-85 AA. "Foundation earth electrode – Planning, execution and documentation," Standard DIN 18014, Mar. 1, 2014.

[11] M. Mokhtari, Z. Abdul-Malek, and G.B. Gharehpetian, "A critical review on soil ionisation modelling for grounding electrodes," *Archives of Electrical Engineering*, vol. 65, no. 3, pp. 449–461, 2016, doi: 10.1515/aee-2016-0033.

[12] E. Musiał, "Measurement of earth resistance," *SEP INPE*, vol. 45, pp. 53–56, 2002.

[13] Dehn Polska. "Foundation earth electrodes." [Online]. Available: https://szkolenia.dehn.pl/pliki/publikacje/ds162_uziomy_fundamentowe_pl.pdf [Accessed: 22. May. 2020].

[14] A. Dąda, P. Błaut, and K. Sidor, "The role of equipotential bondings as a measure of protection against electric shock by the example of special installations," in Proc. of *SPIE 11176*, 2019, pp. 83–93, doi: 10.1117/12.2536726.

[15] Technical Committee No. 55 (PKN/KT 55). "Low-voltage electrical installations – Part 5–54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors," Standard PN-HD 60364-5-54, Aug. 26, 2011.

[16] Elko–Bis Systemy Odgromowe. "Lightning masts on a foundation." [Online]. Available: https://tinyurl.com/38xnn6xj [Accessed: 22. May. 2020].

[17] Alumast. "Composite lightning masts." [Online]. Available: https://tinyurl.com/2t832n34 [Accessed: 22. May. 2020].