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doi:10.15199/48.2016.12.67

Induced and ground potential voltage components in analysis of separation distance for lightning protection in buildings

Abstract. *The paper presents numerical analysis of voltages between LPS and nearby electrical equipment, and separation distances necessary to prevent dangerous sparking during direct lightning strikes. The analysis is focused on the role of induced and ground potential voltage components. The computation of voltages was carried out with specialized software that uses advanced numerical methods based on electromagnetic field theory approach. Based on the results sparking distances were calculated and compared with separation distances according to EN 62305-3.*

Streszczenie*. Artykuł przedstawia analizy numeryczne napięć pomiędzy LPS a pobliskim urządzeniem elektrycznym oraz odstępów izolacyjnych wymaganych w celu uniknięcia przeskoków podczas wyładowań piorunowych. Analizowano rolę dwu składowych napięcia: indukowanej i związanej z rozkładem potencjału w gruncie. Obliczenia napięć wykonano za pomocą oprogramowania wykorzystującego metody numeryczne oparte na teorii pola. Na bazie wyników wyznaczono odległości przeskoku i porównano je z odstępami izolacyjnymi zgodnie z EN 62305-3. (****Składowe napięcia indukowana i związana z rozkładem potencjału w gruncie w analizie odstępów izolacyjnych do celów ochrony odgromowej w budynkach****).*

Keywords: lightning protection in buildings, separation distance, surge withstand, numerical computations.
Słowa kluczowe: ochrona odgromowa w budynkach, odstęp izolacyjny, wytrzymałość udarowa, obliczenia numeryczne.

Introduction

According to the current legit state of technical knowledge, the basic protection measure against direct lightning strikes to a building structure is external Lightning Protection System (LPS). The recommendations on the design, technical realization, exploitation and maintenance of LPS are included in current international standards [1, 2]. The proper design and use of LPS is important for reduction of life hazard and physical damage to the structure itself and to the content of the structure, including electrical and electronic equipment and systems.

The role of LPS is to intercept lightning strikes and to lead down and dissipate lightning currents in ground safely for living beings, the protected structure and its contents. During this process, the short-term lightning current components cause two major problems:
1) the flow of lightning current in LPS conductors (or in building construction components used as LPS) results in voltage drops (mainly inductive) along these conductors and in loops created by LPS and other conductive installations;
2) the dissipation of lightning current in ground results in potential differences between LPS grounding system components due to non-zero grounding impedance (non-zero impedance of system components and finite soil conductivity).

The voltage differences between LPS components of both these origins result in surge voltages between the LPS components and electrical installations or equipment located near to these components.

The most severe conditions (highest voltages) should be expected for the installations or equipment located close to the point of strike to LPS, since this point would have the highest potential with respect to the common grounding point of electrical installations (main grounding terminal), which is located near the ground level. Such situation occurs typically in case of installations or equipment located on a building roof near a vertical air termination rod [3].

The surge voltage that arises between LPS conductor and nearby electrical installation or equipment may exceed the surge withstand capability of dielectric material (air, concrete, wood etc.) in the place of proximity. In the consequence, the uncontrolled lightning current flow may likely cause damage to the whole electrical installation and equipment connected to the considered element. In order to prevent dangerous voltage sparking, the proper minimal distance should be maintained between LPS and other conductive installations. The minimal distance between two conductive parts at which no dangerous sparking can occur is called *separation distance* [2]. For the purpose of this work, another term, *sparking distance*, is defined. It is the maximal distance between two conductive parts at which sparking can occur. Hence, the separation distance should be greater than the sparking distance.

According to the standard EN 62305-3 [2] the separation distance s can be calculated using the following formula:

$$s = \frac{k_i}{k_m} \cdot k_c \cdot l \tag{1}$$

where: k_i – coefficient dependent on the class of LPS (equal to 0.08 for class I, 0.06 for class II and 0.04 for class III and IV), k_m – coefficient dependent on the electrical insulation of material present at the place of proximity (equal to 1 for air and 0.5 for concrete, brick or wood), l – length of the shortest path along LPS conductors from the considered place of proximity to the nearest equipotential bonding point or earth termination (in m), k_c – coefficient dependent on the current share in the individual LPS conductors of the path l.

For mesh air termination system or many interconnected ring conductors the formula (1) is extended to [2]:

$$s = \frac{k_i}{k_m} \cdot \left(k_{c1} \cdot l_1 + k_{c2} \cdot l_2 + ... + k_{ci} \cdot l_i + ...\right) \tag{2}$$

where: l_i , k_{ci} – respectively, length and coefficient of current share associated with i-th element of the path l.

For meshed air termination system on the roof, the coefficient k_c may be determined as shown in figure 1 [2].

The formulas (1) and (2) were originally introduced in 1980s based on results of simplified calculations performed for very simple structures, due to limited computation power available [4, 5]. The simplification of the formulas relies on the approach that the dependency of the separation distance on the waveform and peak value of surge voltage between two conductive parts is substituted by simple dependency on the current sharing between LPS conductors.

Lately, some more complex numerical computations have been undertook using a computer code that solves complete Maxwell's equations (CONCEPT) [4]. The main objective of the work [4] was to verify the standard EN 62305-3 formulas in case of complex LPS, i.e. mesh air termination on the roof and structures representing metal roof as natural LPS component. The evaluation of separation distances in [4] was based on numerical computations of voltages induced in loops. Based on these voltages the separation distances were calculated using the early established constant area criterion [4, 6].

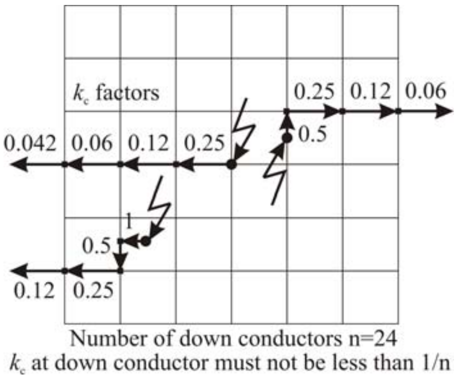


Fig. 1. Determination of coefficients k_c of lightning current share to individual LPS conductors (based on [2])

Indeed, modern computer simulation codes available nowadays make it possible to perform numerical computations of complex electromagnetic problems in very complex structures. They use circuit, transmission line or electromagnetic field theory approaches [7, 8, 9, 10, 11]. In case of separation distance calculation, the electromagnetic field theory approach seems to be the most suitable. It allows for straightforward taking into account all the electromagnetic couplings and phenomena in complex wire structures [4, 9, 10, 11]. However, even now most of the analyses performed using such software is limited to either only aboveground [4, 10] or only underground [9] structures.

This is also in the case of separation distance computations presented in [4], where furthermore, ground was assumed as ideal, perfectly conductive plane. The computations in [4] were performed for structures of different size and height for only one lightning current waveform 0.25/100 μs, which is the standard (EN 62305-1 [1]) representation of subsequent return stroke current.

This paper presents results of numerical computations of surge voltages and sparking distances with using constant area criterion and specialized software (CDEGS) based on electromagnetic field theory approach. In these computations, however, both aboveground and underground parts of the structure in concern have been taken into account and realistic (non-zero impedance) ground has been assumed. The analysis presented in the paper concerns also four different current waveforms representing different lightning current components.

The paper is a continuation of earlier author's works on separation distance computation [12, 13, 14, 15, 16]. The supreme goal of all these works as well as the present paper is to find better solutions for estimation of separation distances for engineering-design purposes than provided in the standard [2]. This need is justified by [4, 13, 14, 15, 16], where it was shown that the separation distances evaluated using standard [2] definitions may be under- or over-estimated compared to numerical analysis.

In [12] some preliminary results of numerical analysis regarding the current waveform 10/350 μs (standard [1] representation of first positive return stroke) are presented. Work [13] shows the first attempt to simplify the calculation for the current waveform 0.25/100 μs (standard representation of subsequent negative return stroke). In work [15] the exact numerical computation results for both 10/350 μs and 0.25/100 μs as well as two more different current waveforms for simple inductive loop were presented. Works [14, 16] consider the influence of cable routing (simple inductive loops and complex structures) and lightning current waveform on the separation distance.

Computation methodology

The computations of surge voltages at the considered places of proximity were performed using HIFREQ software. The program is a part of large specialized software package CDEGS, which offers great possibility of numerical computations of current and potential distributions in complex wire structures (including their above- and under-ground parts), electric and magnetic fields in and around the structures as well as some other auxiliary computations, e.g. Fourier transformations.

The computation method employed in HIFREQ [17] is based on two-potential (scalar and vector) electric field integral equations (derived from full Maxwell's equations) solved numerically using method of moments [17, 18]. The two-potential equations are formulated for a user-defined 3-dimensional network of interconnected thin, cylindrical conductors (subdivided in segments of appropriate length and radius), located in multi-layered media (air and/or one or more layers of soil). The electrical parameters (resistivity, permittivity, permeability) of the conductors and of the media are defined by the user [17]. The electric filed integral equations are formulated in frequency domain and so the computations in HIFREQ. The time-domain solutions are obtained based on Fast Fourier Transform (FFT) of the source signal (current, voltage or electromagnetic field), performing the frequency domain computations in HIFREQ for harmonic sources and subject the results for Inverse Fast Fourier Transform (IFFT). The operations of Forward and Inverse FFT have been performed using FFTSES [19], which is also a part of CDEGS software package.

The source signal for the computations was the time-domain lightning current waveform injected into the structure at the point of strike using an ideal current source. The current waveform at the attachment point was assumed as arbitrary (as introduced in the standards [1, 2]).

The influence of current distribution in lightning channel was disregarded in the computations. Simple calculation with using 10 m long conductor attached to the point of strike (with the current source at the top) showed that the peak values of obtained voltages differ not more than 8 % compared to the case without the conductor. Only in case of current waveform 0.25/100 μs the difference was larger, about 30 %. The observed differences can be associated mainly with the change of lightning current wave at the attachment point due to reflection phenomena. These effects of current distribution in lightning channel are not in the scope of the paper, however further studies are needed.

The lightning current waveform was described using the following standardized formula of EN 62305-1 [1]:

$$i(t) = \frac{I}{\eta} \cdot \frac{(t/\tau_1)^{10}}{1+(t/\tau_1)^{10}} \cdot e^{-t/\tau_2} \tag{3}$$

where: I – peak value of the current wave, η – correction factor, τ_1 – front time constant, τ_2 – tail time constant.

The values of the parameters used in formula (1) were set according to the standard [1] requirements (for LPS

class IV) or adjusted so that to obtain the following impulse current waveforms:
1) 10/350 μs, 100 kA – standard [1] representation of first positive return stroke current,
2) 4/200 μs, 75 kA – representation of return stroke current of moderate front time,
3) 1/200 μs, 50 kA – standard [1] representation of first negative return stroke current,
4) 0.25/100 μs, 25 kA – standard [1] representation of subsequent negative return stroke current.

According to the thin wire approach applied in HIFREQ, the considered building structures were composed of cylindrical conductors. It was assumed that natural building components (reinforcement and foundation grounding) are used as LPS. These components were modeled as galvanized steel conductors of approximate radius, according to [17]. Electrical installations were defined as copper insulated conductors, and equipment chassis as aluminium wires at the edges. The vertical air termination rod on the roof was set as copper conductor.

A single layer ground model was chosen and soil was assumed as poor, dry or moderately humid, with resistivity 500 Ωm, relative permittivity 10 and relative permeability 1.

The conductors of the considered structures were subdivided in segments with lengths not exceeding $\lambda/10$, where λ is the wavelength of the highest considered frequency. The highest frequency corresponding to 0.25 μs impulse current front time was 32,768 MHz, which results in the wavelength of about 9 m in air and 2.5 m in soil. Hence, the segment maximum lengths were set to 0.9 m and 0.25 m respectively.

Once the time domain surge voltages at the considered places of proximity in the structures had been computed, the sparking distances were determined using constant area criterion [4, 20]. According to the criterion, the spark between two electrodes subjected to unipolar surge voltage will occur if particular value of integral A is reached (Fig. 2):

(4) $$A = \int_{t_1}^{t_2} \left[u(t) - U_0 \right] \cdot dt$$

where: U_0 – static (DC) voltage breakdown.

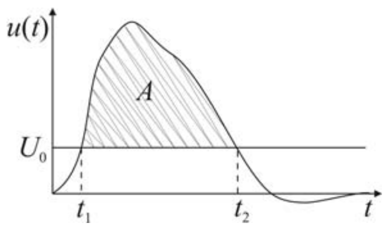


Fig. 2. Illustration of constant area criterion

The relations between A, U_0 and sparking distance d (distance at which spark/discharge under impulse or DC voltage occurs) are well established based on experimental tests and are widely known in literature [20, 21, 22, 4]:

(5) $$A = 590 \cdot d$$

(6) $$U_0 = 630 \cdot d$$

(7) $$U_0 = 2 + 534 \cdot d \quad \text{for } 0.25 \le d \le 2.5$$

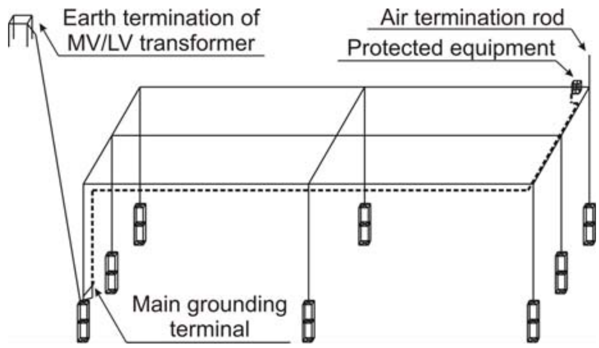
where: A (kV·μs), U_0 (kV), d (m).

In this work, the sparking distance d was computed numerically based on equations (4), (5) and (7) using time domain surge voltages at the places of proximity.

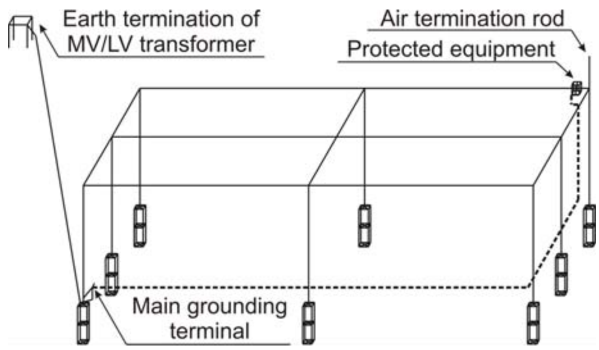
Examined configurations

The considered building structure is a large hall with dimensions of 48 x 24 m and height 12 m. It is composed of natural LPS (class IV) with natural type A earth termination system. Electrical equipment in the building is supplied with underground power line from MV/LV transformer located in about 60 m distance. On the roof of the building an examined electrical equipment is located. The equipment is protected against direct lightning strikes by vertical air termination rod. Direct lightning strike to the air termination rod is assumed. The analysis is focused on evaluation of separation distance between the vertical air termination rod and the protected equipment (Fig. 3).

a) Configuration A



b) Configuration B



c) Configuration C

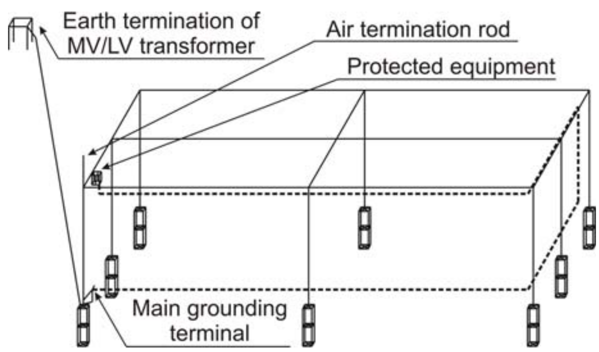


Fig. 3. Locations of the protected equipment on the building roof and configurations of its PE wire path (dash line) inside the building

The analysis was carried out for three different paths, along which the power supply cable to the protected equipment was laid down (Fig. 3). For simplicity only the PE

(Protective Earth) wire of the cable was included in the simulation model. Hence, the PE wire paths corresponded to different mechanisms, by which the surge voltage was produced: magnetic induction in loops associated with ground potential difference between extreme foundation grounding electrodes (configurations A and B, Fig. 3a, 3b), and magnetic induction in loop only with no ground potential difference (configuration C, Fig. 3c).

The aim of this study was to determine the worst case conditions for surge voltage sparking exposures related to cable routing and to the main origin of their generation, i.e. magnetic induction in loops and ground potential rise due to finite soil conductivity, which may have significant influence on the separation distance, as it was shown in [12, 13].

Surge voltage computation results

The computed time-domain voltages between the air termination rod and the protected equipment for configurations (A, B and C) from figure 3 and for different lightning current waveforms are presented in figure 4.

The computation results show that for every considered lightning current impulse the voltages produced in configurations A and B of the PE wire have very similar waveforms. They differ only in the peak value. These differences, however, are significant only for longer rise-time current impulses (10 μs and 4 μs) and become less pronounced in case of short rise-time currents (0.25 μs).

The voltage generated in configuration C is generally different than that produced in the other two (A and B). The waveform of configuration C voltage for longer rise-time currents (10 μs) corresponds well with the waveforms produced in configurations A and B. However, for short rise-time currents (1 μs and 0.25 μs) the voltage waveforms obtained for configuration C are deformed by oscillations. These oscillations arise due to travelling wave phenomena in the relatively long PE wire, about 150 m (48 + 24 + 12 + 24 + 48 = 156, Fig. 3c). The resonant frequency can be seen in figure 4c. It is about 500 kHz, which corresponds to 600 m wavelength. The length of the PE wire is a quarter of this wavelength. It should be noted also that the half cycle of the oscillation, 1 μs, corresponds to the impulse current rise-time. Illustration of this situation is shown in figure 5.

The voltage generated in configuration C is mainly of inductive nature. It is produced in large loop formed by the LPS down conductor located directly beneath the vertical air termination rod and the PE wire. From figure 4a and 4b it can be seen that this voltage is of negative polarity with respect to the voltages produced in configurations A and B.

The voltage generated in case of configuration A and B is a superposition of two components: 1) voltage induced magnetically in the loop formed by the LPS down conductor beneath the vertical air termination rod, ground and the PE wire, 2) ground potential difference between the two foundation earth electrodes located beneath the air termination rod and the main grounding terminal. For a given lightning current impulse, the component related to ground potential difference is the same for both configurations, A and B.

If to assume that the induction component is of opposite polarity to ground potential component (as it was obtained for configuration C, Fig. 4a, 4b), the lower voltage produced for configuration A compared to B can be explained by its higher induction component (larger loop) with respect to the same value of ground potential component.

The differences in the peak values of voltages produced for configurations A and B are less pronounced in case of short rise-time current impulses (Fig. 4c, 4d) compared to longer rise-times. This can be explained by smaller effective area of lightning current dissipation by grounding system in case of shorter rise-time current pulses. Hence, the ground potential component for short rise-time currents is much higher than for long rise-time. Consequently, the induction component is much less visible in the total voltage.

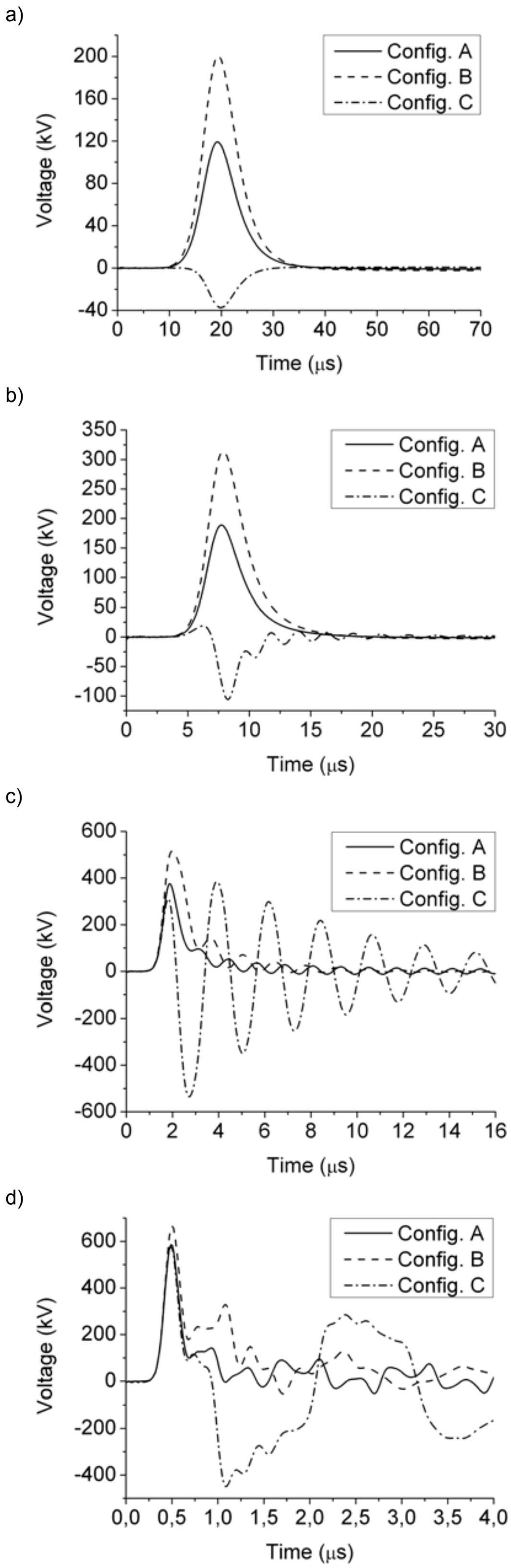


Fig. 4. Voltages between the air termination rod and the protected equipment for different lightning currents: a) 10/350 μs – 100 kA, b) 4/200 μs – 75 kA, c) 1/200 μs – 50 kA, d) 0.25/100 μs – 25 kA

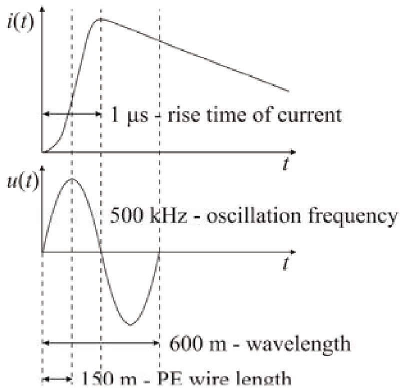


Fig. 5. Illustration of voltage travelling wave in PE wire observed in configuration C for 1/200 µs lightning current (Fig. 4c)

Sparking and separation distance calculation results

Calculation of sparking distance in case of oscillatory type voltage waveforms (configuration C in figures 4c and 4d) is problematic, since constant area criterion generally applies to unipolar impulses. However, for the purpose of rough approximation in this work such calculation was done. In the approximation, it was assumed that each subsequent oscillatory pulse of the same polarity as the first one (larger than static DC voltage breakdown U_0) was integrated and added up to the total value of area A (Fig. 2). Furthermore, this calculation was done separately for oscillatory pulses of positive and negative polarity and the larger value from these two was taken as the final value of sparking distance.

The illustration of the computed sparking distances for the considered lightning current impulses and for the examined configurations (Fig. 3) are presented in figure 6. These results generally reflect the features and characteristics of the computed voltages observed in the previous section. In particular, the resonance effects observed for short lightning current front times (1 µs and 0.25 µs) result in sudden increase of sparking distance for these current waveforms.

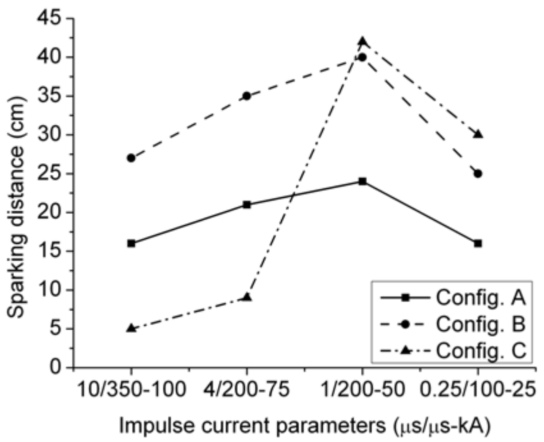


Fig. 6. Sparking distance d for different lightning currents estimated using constant area criterion based on computed voltages (Fig. 4)

The detailed results of calculation of sparking distances are shown in table 1.

The last column in the table presents the values of separation distance calculated according to standard EN 62305-3 [2] formulas (1) and (2). There are two values of separation distance in table (1), associated to two EN 62305-3 standard ways of calculation of coefficient k_c of current share in the individual LPS down conductors. The first way of k_c calculation is shown in figure 1. In case of lightning strike to the corner, the total lightning current is equally divided between 3 conductors (two edges of the mesh air termination and the down conductor beneath the striking point). Hence the current share in the LPS down conductor beneath the air termination rod equals to k_c = 0.33. This is valid in case of all of the considered configurations (A, B, and C).

The other way to determine the current share coefficient is using the following formula [2]:

$$k_c = \frac{1}{2n} + 0.1 + 0.2 \cdot \sqrt[3]{\frac{c}{h}} \tag{8}$$

where: n – total number of down conductors, c – distance of the down conductor to the next down conductors, h – spacing (or height) between ring conductors.

In all the considered configurations (A, B and C) n = 8, c = 18 m (average from 24 m and 12 m) and h = 12 m. Hence, k_c = 0.39.

According to formula (2), k_i = 0.04 (class IV), k_m = 1 (air insulation), k_{c1} = 1, l_1 = 1 m, l_2 = 12 m. Hence, s = 20 cm (for k_{c2} = 0.33) and s = 23 cm (for k_{c2} = 0.39).

Table 1. Computed sparking distances for different lighting current impulses and different configurations of the PE wire (Fig. 3)

Lightning current parameters	Sparking distance d (cm)			Separation distance s (cm)
	A	B	C	acc. to EN 62305-3
10/350 – 100 kA	16	27	5	20 (k_{c2} acc. to Fig. 1) 23 (k_{c2} acc. to (8))
4/200 – 75 kA	21	35	9	
1/200 – 50 kA	24	40	42	
0.25/100 – 25 kA	16	25	30	
Worst case	24	40	42	23

In order to avoid sparking, the necessary separation distance s should be larger than the computed sparking distance d. The shaded areas in table 1 show the cases, in which this condition is not fulfilled (if the EN 62305-3 standard formulas are to be used). In some of the cases, the computed distance d, at which sparking may occur, is nearly twice as large as the separation distance s calculated based on the standard formulas.

Conclusions

The paper presented the analysis of time domain voltages produced between the vertical air termination rod and the protected equipment located on the roof of a large building during direct lightning strike to the rod. Along with and based on these voltages, sparking distances were also estimated using constant area criterion. The sparking distances were analyzed in connection to the problem of proper evaluation of separation distances necessary to maintain in order to prevent dangerous sparking.

The analysis was focused on the role of two components of the total voltage at the considered place of proximity: 1) voltage induced in loops formed by LPS down conductors, ground and the PE wire of the cable supplying the protected equipment, 2) ground potential difference as a result of non-ideal (non-zero) grounding impedance.

The analysis was an attempt to determine the worst case conditions that may occur in the considered building structure, depending on the PE wire path inside. The worst case was generally turned to be associated with the configuration B, for which both the main components of surge voltage (inductive and ground potential) was present, and for which the PE wire was located close to the ground level. However, the results obtained for configuration C clearly show that the general observations may be misleading if resonance and travelling wave phenomena appear. Such situation occurs when the path of the travelling wave (doubled PE wire length) is comparable to the half of the wavelength that corresponds to the rise-time of the current impulse (oscillation frequency).

The confrontation of the computed sparking distances with the separation distances evaluated based on EN 62305-3 standard methods shows that the standard methods might sometimes lead to underestimation of the necessary separation distance. The worst case value of the computed sparking distance was nearly twice as large as the standard-based separation distance.

In all the cases analyzed in the paper, as well as in all the previous author's works [12, 13, 14, 15, 16], the highest values of sparking distance was associated to 1/200 μs 50 kA lightning current impulse, i.e. the standard representation of first negative return stroke current.

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