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Danger of flashovers to electric equipment located on roofs of buildings struck by lightning

***Abstract**. Threats of flashovers to electrical equipment located on roofs of buildings struck by lightning and application of different methods for estimation of separation distances for protection of this equipment are analyzed and compared. Large, few-storey buildings with different external LPS (Lightning Protection Systems) are taken into considerations. The analyses are based on the results of numerical calculations, confronted with the results of approximate procedures proposed in the European and international standards on lightning protection EN/IEC 62305-3.*

***Streszczenie.** Analizowane są zagrożenia przeskokami iskrowymi do urządzeń i instalacji elektrycznych na dachach obiektów budowlanych trafionych przez wyładowania piorunowe oraz różne metody szacowania odstępów izolacyjnych w celu ochrony tych urządzeń. Analizy bazują na wynikach obliczeń numerycznych oraz zaleceniach europejskich i międzynarodowych normach ochrony odgromowej EN/IEC 62305-3. (**Zagrożenie przeskokami iskrowymi do urządzeń elektrycznych zlokalizowanych na dachach budynków trafionych przez wyładowania piorunowe**).*

Keywords: flashovers, separation distance, lightning strike to a building, numerical calculation.
Słowa kluczowe: przeskoki iskrowe, odstęp izolacyjny, wyładowanie pioruna w obiekt budowlany, obliczenia numeryczne.

Introduction

During direct lighting strike to a building structure lightning current flows through LPS (Lightning Protection System) and/or construction elements. This current flow creates potential differences [1-3], which might lead to flashovers between parts of LPS and elements of electrical systems or installations running nearby.

The danger is particularly high in buildings with installations and/or equipment on roofs. In case of roof fixtures isolated from the LPS, e.g. antennas protected with vertical air termination rods, there is a risk of damage to these fixtures [4]. In order to prevent flashovers a minimal, so-called separation distance should be maintained between conductors caring lightning current and the nearest parts of protected systems and installations.

Methods of estimation of separation distances

In practice, the separation distance is estimated using simple procedures proposed in the international standard on lightning protection [5]. According to the standard, the separation distance d is described by the following formula:

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

where: k_i – coefficient dependent on the LPS class, equal to: 0.08 (class I); 0.06 (class II) or 0.04 (class III and IV), k_m – coefficient dependent on the type of isolation material at the place of proximity, equal to: 1 (air) or 0.5 (concrete, brick, wood), l – length, in meters, of the shortest path along LPS conductors from the considered place of proximity to the nearest equipotential point or earth termination, k_c – coefficient of lightning current division along the path l.

For buildings with mesh air termination system or many interconnected ring conductors, where current division at particular floor is different, the following formula is used [5]:

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

where: l_i, k_{ci} – respectively length and coefficient of current division for i-th part of the path l.

Calculation of separation distances with these formulas reduces to the estimation of the coefficients k_c of current division between the LPS conductors. These coefficients can be calculated numerically [6] or in a simplified way, according to procedures provided in the standard [5].

Another way for estimation of separation distance is based on the surge voltage between two approaching points (electrodes). The safe, separation distance between electrodes is dependent on the waveshape and the peak value of this voltage as well as the electrical withstand of isolating material. The last depends on the surge voltage as well. For solving of this problem, the so-called "constant area criterion" is used [7-8]. According to this criterion, a flashover for impulse voltage of any waveshape will occur only if a certain value of area A is reached (Fig. 1):

$$\int_{t_1}^{t_2} [u(t) - U_0] \cdot dt = A \tag{3}$$

where: U_0 – static flashover voltage between electrodes (breakdown voltage for dc voltage).

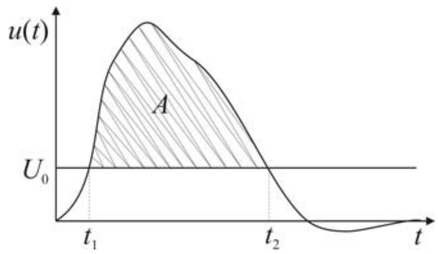

Fig. 1. Illustration of the constant area criterion

Based on experimental test results carried out for rod electrodes exposed to negative impulse voltages, relations between A, U_0 and a flashover distance s between electrodes were fund [7, 9]:

(4) $A = 590 \cdot s$ [7, 8, 10]

(5) $U_0 = 630 \cdot s$ [8]

(6) $U_0 = 2 + 534 \cdot s$ 0.25 ≤ s ≤ 2.5 [9, 10]

where: A (kV·µs); U_0 (kV); s (m) is the distance between electrodes, at which the flashover occurs; the separation distance d should be greater than the flashover distance s.

Estimation of the flashover distance s is usually done based on formulas (3)-(5) for the surge voltage wave

approximated with rectangular, triangular or trapezoidal shape [8, 10]. In this work, the flashover and separation distances have been estimated as follows:
1) the separation distance d - according to the standard EN 62305-3, with formulas (1)-(2) and simple procedures for estimation of coefficients k_c of current division [5];
2) the flashover distance s - according to the constant area criterion (3)-(6), based on numerical calculations of surge voltages between the considered approaching points.

Method of numerical calculation

Numerical calculations were carried out using HIFREQ software. The calculation method is based on two-potential electric field equations derived from full Maxwell's equations in frequency domain and the method of moments. The equations are formulated for a user-defined 3-dimensional network of interconnected thin, cylindrical segments located in multi-layered media (air and a few layers of soil). The electrical parameters of the network as well as the media are also arbitrary defined by the user [11].

In calculations, lighting strike was represented with an ideal current source connected to the point of strike. Exact calculations were performed for the first lightning return stroke represented with standardized wave of 10/350 μs [12]. Based on these results, some approximate calculations were also performed for the subsequent return stroke represented with 0.25/100 μs wave [12].

The waveshapes of the lightning return stroke currents were defined using the following standardized formula [12]:

$$i = \frac{I}{\eta} \cdot \frac{\left(t/\tau_1\right)^{10}}{1 + \left(t/\tau_1\right)^{10}} \cdot e^{-\frac{t}{\tau_2}} \tag{7}$$

where: I – peak value of the lightning return stroke current impulse (dependent on the LPS class), η – correction factor, equal to: 0.93 (first stroke) or 0.993 (subsequent stroke), τ_1 – front time constant, equal to: 19 μs (first stroke) or 485 μs (subsequent stroke), τ_2 – tail time, equal to: 0.454 μs (first stroke) or 143 μs (subsequent stroke).

Building structures in concern

Two types of building structures were concerned:
- building with dimensions of 50x20x20 m, with LPS of class II (mesh air termination of 10x10 m) and type B earth termination (ring electrode buried at 0.7 m depth);
- hall with dimensions of 48x24x12 m, with natural LPS of class IV (mesh air termination of 24x12 m) and natural type A earth termination (foundation earth electrodes).

Thin-wire representations of these structures created in HIFREQ environment are presented in Fig. 2.

Both structures are equipped with similar network of conductors inside, which represents the main branches of electrical installations. For simplicity, only the protective earth (PE) conductors are taken into account. The arrangement and earthing place of the PE conductor from the incoming external power line is also identical in both cases. The earth termination of the transformer station, in a distance of about 60 m, is taken into account.

In each structure, one branch of the PE conductor network is led from the inside to the roof and is connected to electrical equipment located on the roof. It was assumed that the equipment is situated inside the protection volume [5] created by a vertical air termination rod located nearby (in a 1 m distance). Voltages between this vertical air termination rod and the protected equipment during direct lightning strike to this rod were calculated and analyzed.

a)

b)

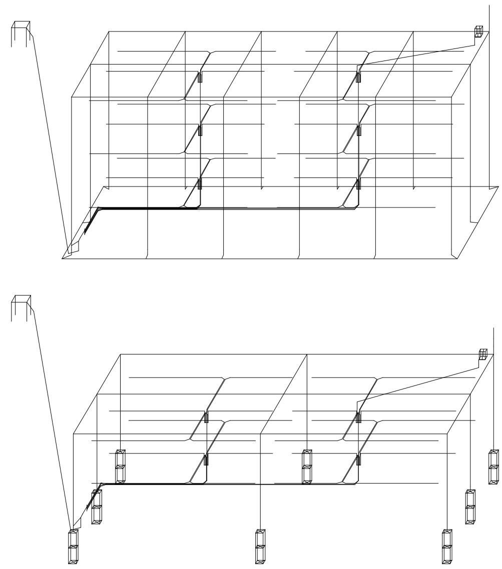

Fig. 2. Thin-wire representations of building structures created in HIFREQ: a) building - 50x20x20 m; b) hall - 48x24x12 m

The calculations were carried out for different locations of the arrangement "vertical rod - protected equipment" on the roof. These scenarios are presented in Fig. 3.

a) b)

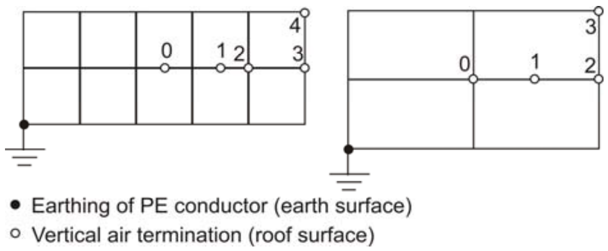

Fig. 3. Various locations of the arrangement „vertical air termination rod - protected equipment" on the roofs of buildings from Fig. 2 (points of lightning strike)

In calculations two types of ground were also assumed: lossy ground with resistivity of 50 Ωm or 500 Ωm and ground close to ideal with 0.0001 Ωm resistivity.

Results – building from Fig. 2-3 a)

Exact numerical calculations of voltages between the vertical air termination rod and the protected equipment were carried out for current impulse representing the first lightning return stroke (10/350) with 150 kA peak value, which corresponds to the LPS of class II according to the standard [12]. The resulting surge voltage for 500 Ωm soil resistivity and localization of the air termination rod in point 1 (Fig. 3a)) is presented in Figure 4 (solid line).

The dashed line is the voltage obtained as a product of derivative of the first return stroke current impulse and a scaling factor M adjusted so that the peak value of the product was close to the peak value of the voltage calculated with HIFREQ. As the figure shows, the result of this approximation (based on derivative of lightning current pulse) is in agreement with exact calculation using HIFREQ.

This approximation was used in calculations of surge voltages between the air termination rod and the protected equipment for the subsequent lightning return stroke (0.25/100). In this case, the derivative of the subsequent stroke current impulse was multiplied by the same scaling factor M as for the first stroke. The advantage of this approximation is the reduction of calculation time. Exact calculation using HIFREQ for the subsequent stroke is very time consuming due to large number of frequencies for calculation. Verification of this approximation with exact HIFREQ calculation is the subject for future works.

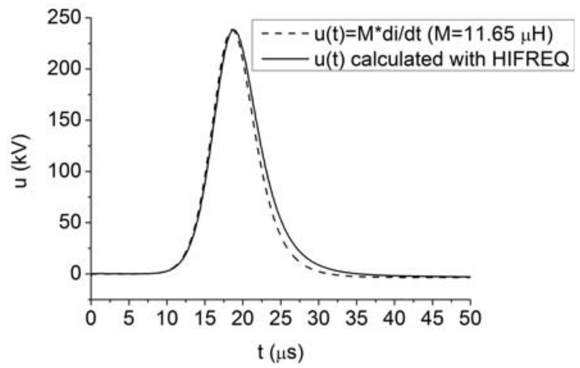

Fig. 4. Voltage between the air termination rod and the protected equipment for 500 Ωm soil resistivity and localization of the air termination rod in point 1 (Fig. 3a))

In relation to the building (Fig. 2-3a)), this approximation was used for the subsequent lightning return stroke current of 37.5 kA peak value (LPS of class II).

Once, the surge voltages between the air termination rod and the protected equipment have been calculated, it was possible to estimate the flashover distance s based on the constant area criterion. Specific values of the area A corresponding to different values of static breakdown voltage U_0 were calculated (3) and related to the flashover distance s according to (6). Example results for 500 Ωm soil resistivity and localization of the air termination rod in point 1 (Fig. 3a)) are presented in Fig. 5.

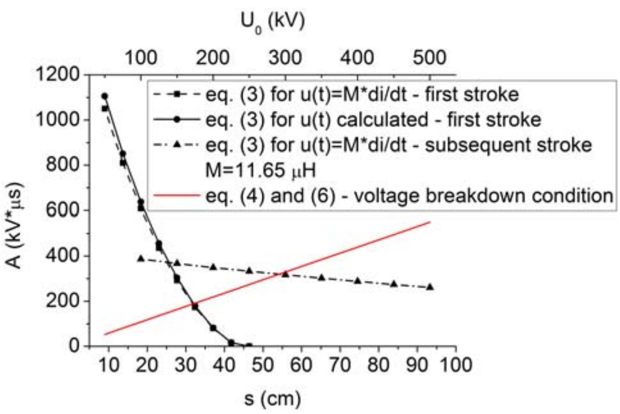

Fig. 5. Relations between A, U_0 and s for 500 Ωm soil resistivity and rod localization in point 1, and voltage breakdown conditions

It is seen that for the first lightning stroke the relations estimated based on exact numerical calculation and derived from the lightning current impulse are very close to one another. More significant divergence is observed for lower values of s and U_0. It is clear, since the corresponding voltage waves differ more significantly at their tails and for lower voltages (see Fig. 4).

Figure 5 shows that for the first lightning stroke the separation distance d between the rod and the protected equipment should be greater than about 32 cm (the values of A calculated lower than causing breakdown). For the subsequent stroke the conditions are more severe, resulting in the separation distance greater than about 56 cm.

Deeper analysis of the calculation results indicates that the ratio of the flashover distance estimated for the subsequent lightning stroke to the flashover distance calculated for the first stroke is about 1.7 – 1.75.

The peak values of the calculated surge voltages for all the localizations of the air termination rod (Fig. 3 a)) and the related values of the flashover distance s are presented in Table 1. The results concern the subsequent return stroke, as proved to being more severe. Along with these results, the values of the separation distance d estimated according to the standard (EN 62305-3) are presented.

Table 1. Peak values of surge voltage, flashover distance s (acc. to constant area crit.) and separation distance d (acc. to EN 62305-3)

Localization of air termination rod (Fig. 3a))	Peak value of surge voltage (kV)	Flashover distance s (cm)	Separation distance d (cm)
Subsequent lightning stroke			
0	2030	46	57
1	2440	55	42*
2	2220	51	42*
3	2590	60	47,5*
4	3010	70	47,5*
* – separation distance d too small, flashovers might occur			

First, it shall be noted that the larger is the distance between the location of the protected equipment and the earthing place of the PE conductor (Fig. 3a)), the higher is the distance s that might result in a flashover.

The results show also that only for the rod localization in point 0 the separation distance d estimated according to the standard might be enough to avoid flashovers. For all the other localizations the separation distance d is too small. Moreover, there is no correlation between the peak value of surge voltage and the separation distance d. On the other hand, the relations between the flashover distance s and the peak value of surge voltage for either the first and subsequent strokes are linear, in the considered range. The above facts indicate that the standard procedures for estimation of separation distances are questionable.

Results – hall from Fig. 2-3 b)

Influence of soil resistivity on the surge voltages and the flashover distance s between the air termination rod and the protected equipment have been analyzed for the large hall presented in Fig. 2b). The exact numerical calculations with HIFREQ were carried out for the first lightning return stroke current (10/350) with 100 kA peak value, which corresponds to the LPS of class IV [12]. The calculations for the subsequent return stroke current (0.25/100) with 25 kA peak value (LPS of class IV) were performed approximately in the same way as described in the previous section.

First, it shall be pointed that the accuracy of calculations for the hall might be worse than for the building, particularly for higher soil resistivity. Just to give some illustration, Figure 6 shows the relations between A, U_0 and s, calculated according to the constant area criterion (3) for 500 Ωm soil resistivity and rod localization in point 3 (Fig. 3b)), along with the voltage breakdown conditions (4)-(6).

Compared to Fig. 5, there is much more divergence between the two curves, calculated exactly with HIFREQ and derived from the current impulse. This is due to the fact that the curve derived from the current impulse does not take into account resistive coupling, which is significant for type A earth termination. Fortunately, significant divergence is observed only for relatively low values of s, far from the point of crossing with the voltage breakdown condition.

As shown in Fig. 6, the flashover distance is really small. Actually, in all the considered cases the flashover distance regarding the first lightning stroke was lower than 25 cm.

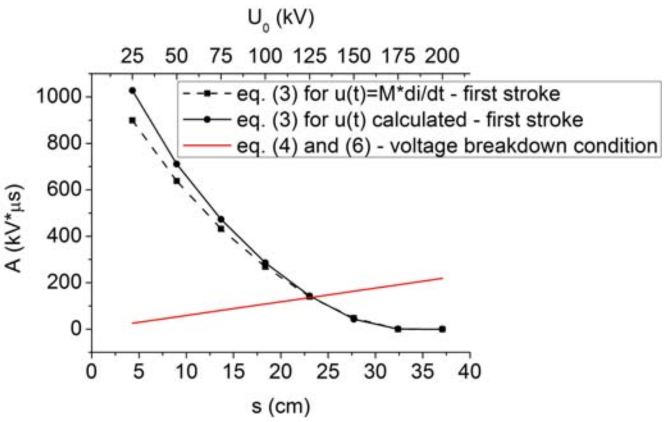

Fig. 6. Relations between A, U_0 and s for 500 Ωm soil resistivity and rod localization in point 3, and voltage breakdown condition

Relations between the flashover distance s and the peak value of surge voltage for the first and subsequent strokes are presented in Fig. 7. As shown, both relations are linear. Small nonlinearities are due to rounding during reading of s and U_{max} values from diagrams (such as presented in Fig. 6). The ratio of the flashover distance estimated for the subsequent stroke to the flashover distance calculated for the first stroke for the hall was about 1.7 – 1.8.

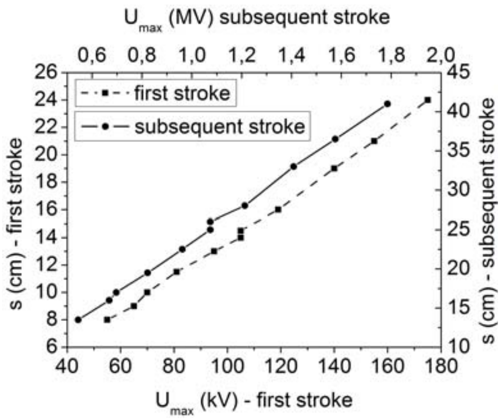

Fig. 7. Relations between the flashover distance s and the peak value of surge voltage for the first and subsequent strokes

A summary of the results of calculations of the flashover distance s between the air termination rod and the protected equipment for the subsequent stroke are shown in Fig. 8. The figure shows also the separation distance d estimated according to the standard (EN 62305-3).

For localizations of the air termination rod in points 0 and 1, the value of the separation distance d estimated according to standard 62305-3 may be enough to avoid flashovers. However, for localizations 2 and 3, farther from the earthing place of the PE conductor, the separation distance may be appropriate only for ideal ground or relatively low soil resistivity (up to about 50 Ωm). In case of higher resistivity soil for these localizations, the separation distance is too small, what may result in flashovers.

For high resistivity soils there is also no correlation between the flashover distance s calculated according to the constant area criterion and the separation distance d estimated according to standard 62305-3.

Conclusions

The results of this work indicate that the procedures for estimation of separation distances provided in the standards on lightning protection work well only for ideal or low resistivity soils (up to about 50 Ωm) and for relatively close distance between the protected equipment (air termination rod) and the earthing place of the PE conductor. This conclusion is valid not only for buildings with type A earth terminations but also for type B, ring earth electrodes (direct metallic interconnection of the entire system).

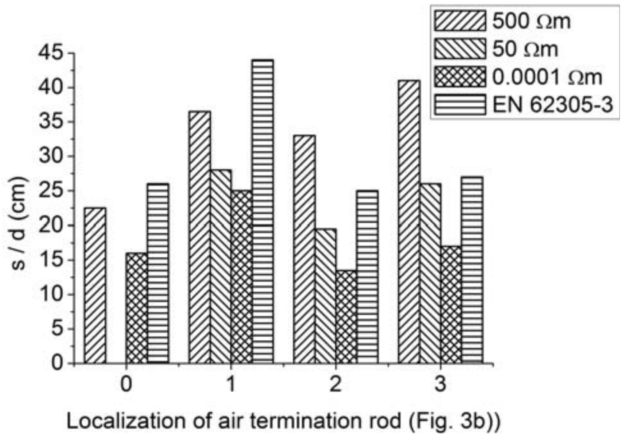

Fig. 8. Values of the flashover distance s calculated for the subsequent stroke and different soil resistivity, and the separation distance d estimated according to standard EN 62305-3

There is a necessity to develop better procedures for estimation of separation distances. Such procedures shall be as simple as possible, however they should take into account also soil resistivity and location of the protected equipment with regard to the earthing place of its PE conductor (or maximal dimensions of building structure).

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