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Influence of Lightning Current Waveshape on the Separation Distance Required between Electrical Equipment and Lightning Protection System

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***Abstract*—The object of this paper is to study the effects of lightning current waveshape on the flashover distance between LPS and protected equipment on a building roof, calculated based on constant area criterion and including all electromagnetic couplings between building components. The resulting flashover distance has been related to the separation distance estimated according to standard procedures [3]. The analysis indicates that the most severe condition is related to 1/200 μs lightning current wave, which leads to the highest value of the flashover distance, much higher than the separation distance required by standards. It was shown also that the flashover distance is linearly dependent on the peak values of lightning current and surge voltage between the protected equipment and LPS.**

***Index Terms*—Separation distance, flashovers, sparking, lightning protection.**

I. INTRODUCTION

During lighting strike to a building lightning current flows through an LPS (Lightning Protection System). This process results in potential differences [1], [2], which might lead to flashovers between the LPS components and electrical systems and installations located nearby. The risk of damage is particularly high for systems on a roof. To prevent flashovers a minimal, separation distance has to be maintained.

European and international standard procedures [3] for calculation of separation distances do not take into account some important factors related to ground potential differences and hence, may need revisions [4], [5]. On the other hand, the flashover distance (i.e. the maximal distance at which a flashover might occur) can be defined and calculated according to constant area criterion [6], [7]. Using this criterion it is possible to take into account those and many other factors.

The aim of this paper is to study the effects of lightning current waveshape on the flashover distance calculated based on constant area criterion, including all electromagnetic couplings between building components, and to relate the results to the separation distance estimated according to standard procedures.

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II. SEPARATION DISTANCE ACC. TO EN/IEC 62305-3

According to European and international standards on lightning protection [3], the separation distance s can be estimated with the following formula

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

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 of the shortest path along LPS conductors from the considered place of proximity to the nearest equipotential bonding point or earth termination; k_c – coefficient of current division along the path l.

For mesh air termination system or for many interconnected ring conductors the formula is extended [3]

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

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

Hence, calculation of separation distances reduces to estimation of the coefficients k_c. Fig. 1 illustrates how the coefficients k_c may be determined for meshed air termination system on a building roof [3].

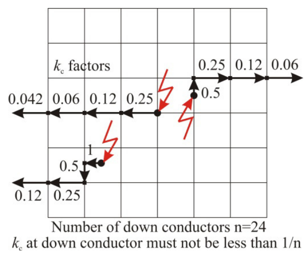

Fig. 1. Determination of coefficients k_c of lightning current division between LPS conductors [3].

III. FLASHOVER DISTANCE ACC. TO CONSTANT AREA CRITERION

To calculate the flashover distance, i.e. the largest distance at which a flashover occurs, the surge voltage between the considered points of proximity (electrodes) has to be determined first. The flashover distance is dependent on the waveshape and peak value of this voltage and the electrical withstand of isolating material. The last is dependent on the surge voltage as well.

To solve this problem, constant area criterion may be used [6], [7]. According to the criterion, for impulse voltage of any waveshape a flashover will occur only if particular value of area A is reached (Fig. 2)

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

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

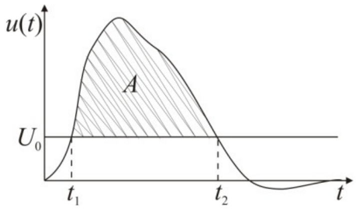

Fig. 2. Illustration of constant area criterion.

Based on the results of experimental tests carried out for rod electrodes exposed to negative impulse voltages (as more severe), relations between A, U_0 and the flashover distance d between electrodes were found [6]–[9]:

$$A = 590 \cdot d\,, \tag{4}$$

$$U_0 = 630 \cdot d\,, \tag{5}$$

$$U_0 = 2 + 534 \cdot d\,; \quad 0.25\text{ m} \le d \le 2.5\text{ m}, \tag{6}$$

Where A (kV·µs); U_0 (kV); d (m) is the maximal distance between electrodes, at which a flashover occurs.

To estimate the flashover distance d the surge voltage wave is usually approximated with rectangular, triangular or trapezoidal shape [7], [9]. In this work, the exact surge voltage waves were determined by numerical calculation.

IV. CALCULATION OF SURGE VOLTAGE AT THE PLACE OF PROXIMITY

For numerical calculation of surge voltages HIFREQ software was used. The computation method employed in the software is based on two-potential electric field integral equations derived based on full Maxwell's equations in frequency domain and solved numerically using 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). Electrical parameters of the network and the media are also defined by the user [10]. Hence, the method is capable to account for all electromagnetic couplings between particular LPS components and protected systems. However, only linear phenomena can be studied.

In calculation lightning return stroke was represented with an ideal current source located at the point of strike on the 3-dimensional thin-wire network (the building in concern). The lightning current waves were described by the following standardized formula [11]

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

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

The parameters in this formula were set according to the standard requirements [11] or adjusted so that to obtain the following short-duration impulse current waveshapes:

1) 10/350 µs, 100 kA – current waveshape of the first positive lightning return stroke [11];
2) 0.25/100 µs, 25 kA – current waveshape of the subsequent negative lightning return stroke [11];
3) 1/200 µs, 50 kA – current waveshape of the first negative lightning return stroke [11];
4) 4/200 µs, 50 kA – current waveshape of lightning return stroke with moderate front time values.

The building structure in concern is a hall of 48 x 24 x 12 m. It is composed of natural LPS of class IV (mesh air termination of 24 x 12 m) and natural type A earth termination (foundation earth electrodes). The thin-wire representation of this structure created in HIFREQ environment is presented in Fig. 3.

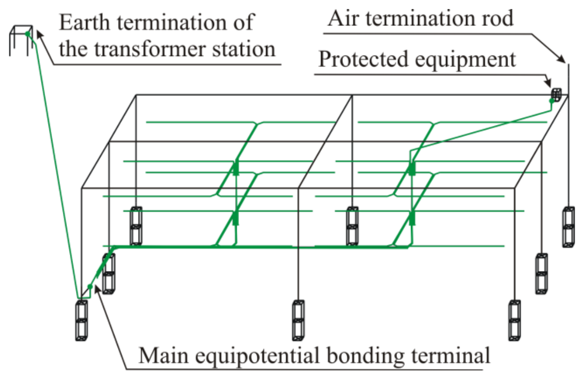

Fig. 3. Thin-wire representation of the building structure in concern created in HIFREQ: hall 48 x 24 x 12 m.

The structure is equipped with network of conductors inside and outside, to represent the main branches of electrical installations. For simplicity, only the protective earth (PE) conductors are included. All the PE conductors from the inside and of the incoming external power line are bonded to one common point, i.e. the main equipotential bonding terminal. The PE conductor of the external power line is connected also to the earth termination of the transformer station, in about 60 m distance (Fig. 3).

One branch of the PE conductor network is led from the inside to electrical equipment located on the roof. The equipment is situated inside the protection volume [3] created by a vertical air termination rod (in 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.

In calculations, uniform lossy soil type was assumed with the following parameters: resistivity 500 Ωm, relative permeability 1 and relative permittivity 10.

V. RESULTS OF CALCULATION, ANALYSIS AND DISCUSSION

The resulting surge voltages between the air termination rod and the protected equipment on the roof for different lightning current waves are shown in Fig. 4.

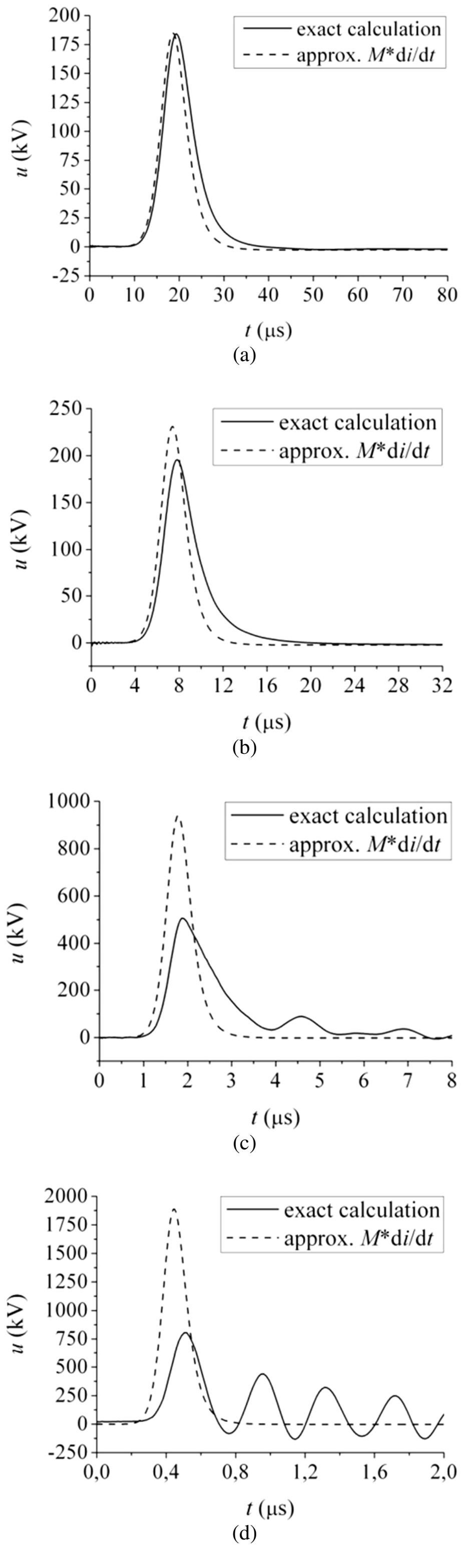

Fig. 4. Surge voltages between air termination rod and protected equipment (Fig. 3), for lightning current waveforms: (a) – 10/350 μs - 100 kA; (b) – 4/200 μs - 50 kA; (c) – 1/200 μs - 50 kA; (d) – 0.25/100 μs - 25 kA.

Along with these voltage waves, there are shown also approximate curves obtained as a product of derivative of the lightning current wave and a multiplication factor $M = 13.54$ μH. The value of M was determined based on the result of numerical calculation related to 10/350 μs lightning current wave, for which the exact and approximated voltages were very similar (Fig. 4 a)). As presented, this approximation is not valid for lightning current waves of shorter front times. The shorter the front time, the difference between the exact and approximated voltage waves is more pronounced. The observed effect may indicate at the role of also capacitive and resistive couplings, as more vivid at higher frequencies.

Based on the results of exact calculation of surge voltages (Fig. 4), specific values of area A corresponding to different values of static breakdown voltage U_0 were calculated according to (3). The static breakdown voltage U_0 was also linked to the flashover distance d according to (6). The results are presented in Fig. 5.

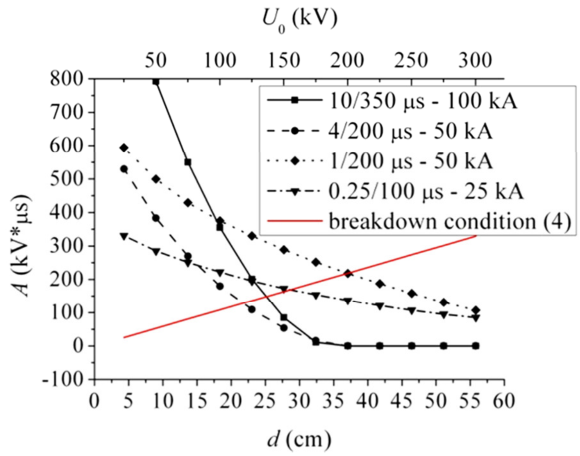

Fig. 5. Relations between integral A, static breakdown voltage U_0 and flashover distance d calculated for exact surge voltage waves (Fig. 4) and voltage breakdown condition acc. to (4).

The crossing points of the $A(U_0)$ relations with the line representing the voltage breakdown condition (4) define the maximal distances, at which flashovers occur. The most severe condition is related to the first negative lightning return stroke, with current waveshape of 1/200 μs (50 kA peak value), as it produces the largest maximal distance for a flashover to occur, about 37 cm. Hence, the separation distance s should be greater then this value.

These results are in contradiction to the lightning protection standard [11], where it is stated that dangerous sparking or flashovers should be attributed to the subsequent negative lightning strokes.

Next, the separation distance s required by lightning protection standards [3] was calculated (Fig. 1, eq. (1)-(2)). Taking the fact that the air termination rod is situated at the building corner, in the worst case the separation distance is equal to: $s = 0{,}04\cdot(1\cdot 100 + 0.5\cdot 1200)/1 = 28$ (cm).

This value is nearly the same as the value of the flashover distance obtained for 0.25/100 μs (25 kA) lightning current wave, $d = 28.7$ cm (Fig. 5). However, comparing to the worst case value of the flashover distance, $d = 37$ cm (for 1/200 μs - 50 kA), it is not enough to provide a safe distance of the protected equipment from the air termination rod. This fact and some other results [4], [5] imply that the standard procedures [3] for calculation of separation distances need revisions.

The surge voltages (Fig. 4) had been obtained under the assumption of linear dependence on the lightning current (they themselves present the situation as if no actual breakdown or flashover occurred). This means that the dependencies of the flashover distance d on the peak value of surge voltage U and on the peak value of lightning current I are of the same kind. The relation between the flashover distance d and the peak value of lightning current I for different current waveshapes are presented in Fig. 6. Table 1 shows the connection between the peak values of lightning current I and of surge voltage U.

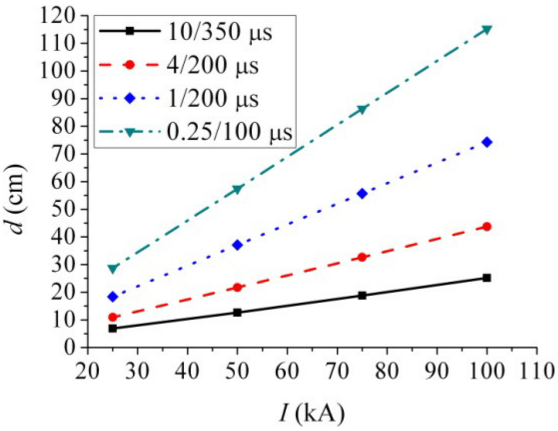

Fig. 6. Relations between the flashover distance d and the peak value of lightning return stroke current I.

TABLE I. CONNECTION BETWEEN THE PEAK VALUES OF LIGHTNING CURRENT I AND OF SURGE VOLTAGE U.

I (kA)	**U (kV)**			
	10/350 μs	**4/200 μs**	**1/200 μs**	**0.25/100 μs**
25	46	98	253	805.5
50	92	196	506	1611
75	138	294	759	2416
100	184	392	1012	3222

The results show that the flashover distance d is linearly dependent on the peak value of lightning current I as well as on the peak value of surge voltage U at the place of proximity for all considered lightning current waves.

VI. CONCLUSIONS

The analysis presented in this paper suggest that the values of the separation distance estimated according to the standard procedures [3] might be too small to guarantee a safe distance of the protected equipment on a building roof from the LPS components and need revisions.

It was shown that the most severe condition (among the considered cases) is related to 1/200 μs (50 kA) current waveshape, for which the flashover distance (37 cm) is much higher than the required [3] separation distance (28 cm).

For all considered lightning current waveshapes the flashover distance d is linearly dependent on the peak values of lightning current I and surge voltage U between the protected equipment and LPS.

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