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Minimum Separation Between Lightning Protection System And Non-Integrated Metallic Structures

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***Abstract*— In the event of a direct lightning strike to a protected building which is integrated with an electrical or electronic system installed on the roof such as roof-top PV system, dangerous arcing may occur between the external lightning protection system (LPS) and the conductive components of the electrical system. To prevent such side flashes, a minimum separation distance between the metallic components and the air termination system is required. Even though, IEC62305-3 Standard provides a formula to specify the necessary separation distance, so far there is no extensive study that has been done to evaluate the suitability of the application of equation to calculate the separation distance, specifically to the safety of electrical systems integrated into the roof top of building. In this study, a new computational method has been developed for calculation of the separation distance between an LPS and metallic components on the roof. In the proposed method which is based on the theoretical background of the IEC62305-3 Standard formula, the break down behavior of the gap geometry between the LPS and the metallic components for the applied voltage across the gap is analyzed. PSCAD software was used to model the LPS and the lightning strokes.**

Keywords— Separation distance; lightning protection system (LPS);constant area criterion;voltage-time law

I. Introduction

In a lightning protected structure, the external Lightning Protection System (LPS) is intended to intercept direct flashes to the structure and conduct this lightning current to the ground without causing dangerous sparking. The external LPS consist of air termination system, down conductor and earth termination system. Air termination system prevents the direct lightning strike to the building by intercepting the lightning strikes and conducts this current through horizontal conductors to the vertical down conductors and disperses the current through earthing system to the soil. Conduction of lightning current through the LPS increases the possibility of side flashes to the metal parts of the building and internal systems. Prevention of such side flashes is recommended in IEC 62305-3 Standard by either keeping a minimum separation distance between the LPS and metallic parts or integrating the LPS to the metallic components [1].

In building-integrated electrical system where parts of the system are installed on the roof, i.e. roof-top PV system, communication installation on the roof or broadcasting cables and components, integrating the LPS to the metallic parts in order to prevent the side flashes will expose electronic and electrical items of the system in to the danger. Therefore, in such cases the only option is to keep a minimum separation distance between LPS and metallic components. Studies on the separation distance between the LPS and the metallic structure on the roof are very important to evaluate the possibility of flashover in the gap distance between LPS and metallic components, and in order to provide an efficient lightning protection system [2].

IEC62305-3 Standard [1] provides a formula to calculate the separation distance to prevent arcing. This formula originally was developed in early 1980s for simple structures [3]. However, several important factors related to the potential differences have not been considered in this formula. Also this standard does not specify the possibility of having electrical system at roof-top such as photovoltaic (PV) panels, wind power generating systems, antenna structures for radio/communication base stations, television and satellite antenna systems, CCTV systems, roof-top sign boards and other lighting systems, which are integrated parts of many modern commercial or even some domestic buildings.

The formula proposed by the IEC62305-3 Standard [1], assumes an unrealistic square wave shape for the lightning current, thus the voltage drop due to that. Such assumption

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deviates the computational model considerably from the real situation. In a cloud-to-ground lightning flash, there are basically three types of possible lightning current wave shapes; in negative ground flashes the first stroke and subsequent strokes and positive ground flashes the usually single current impulse referred as positive stroke [4]. Each of these three types has their own temporal characteristics and amplitude distribution [5]. This shows that the real situation of injected current and the consequent voltage waveform is much more complex than the assumed square wave shape in IEC62305-3 Standard.

The IEC62305-3 Standard also neglects the effects of the earth resistance of the grounding system of the LPS. It is of interest to the engineering community to investigate whether there is a significant difference in the required minimum separation based on the grounding system performance. So far, no quantitative investigation has been done in this regard.

This study has been conducted to address the above technical problems in the field of lightning protection. The significance of such information is highly beneficial in the future due to the growing demand for micro-scale alternative energy sources such as roof-top mounted PV panels and wind energy generation systems. Nowadays, developed computer codes make it possible to revisit the specification of separation distance.

II. THEORY

In the standard IEC 62305-3, the necessary separation distance from the air termination or down conductor is described by following formulae[1] :

$$s = k_i \cdot \frac{k_c}{k_m} \cdot l \qquad (1)$$

Where S is the separation distance in meters, and k_i depends on the selected class of LPS, k_c depends on lightning current flow to down conductors and k_m is related to the insulation material. l is the shortest length along the air termination or down conductor to the nearest equipotential bonding point.

The IEC formulas take the current distribution and insulation properties of LPS into account within the k_c, k_m and k_i coefficients. these coefficients consider the simplified constant steeped lightning current such as 200 kA/μs [6]. However, the actual current in a subsequent stroke to the LPS can be expressed using the mathematical function [7].

Several studies in literature assessed the calculation of separation distance considering the real lightning current wave shape. For example Markowska et al. [8] determined the k_c coefficient by investigating the current distribution in the LPS of a large industrial building both by measurement and modeling. It has been shown that the k_c values obtained by measurement are higher compared to calculation using IEC formula. Also the results of simulation using the mathematical model of lightning current and conductive elements were consistent with measurement results. Moreover, Pablo Gómez [9] simulated a frequency based transient model of lightning current distribution in the LPS of a building using PSCAD/EMTDC. The results validated by means of comparison with the measurement results of the early work of Sowa [10].

Furthermore, the values of k_i in IEC formula implement the breakdown voltage in an air gap geometry. Flowing of the lightning current in the LPS creates potential difference between the LPS and any metal installation on the roof which stresses the gap for separation distance. Thus, types of different gap geometries and the shape of induced voltage in this gap are of deterministic parameters for breakdown. In a study by Ottmar Beierl et al. [11] the k_i coefficient has been assessed by examining the dielectric strength of air gap applying different voltage impulses in sub-microsecond scale.

This study aims to calculate the flashover distance in the gap geometry assuming the gap is stressed by induced voltage due to the flowing of lightning current in the LPS. The value of flashover distance is further compared with the values achieved according to IEC formula.

III. METHODOLOGY

The original physical background of IEC formula for determining the separation distance is based on W. Zischank early work in 1988, which takes the break down behavior and dielectric strength of the gap geometry between LPS and metallic installation into account [3]. Also, the dielectric strength in this gap geometry depends on the voltage wave form [12]. Therefore, determining the separation distance following the original approach in IEC must be conducted by analyzing the induced voltage across the gap [3].

In the basic equation for separation distance in IEC62305-3 standard, the applied voltage across the gap has been simplified to be a rectangular pulse, while in reality this voltage wave shape is due to the injection of subsequent negative stroke lightning current and is not a derivative of ramp function as a simplified lightning current as Figure 1.

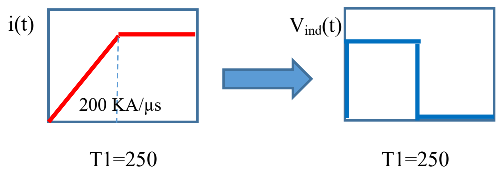

Fig. 1. The rectangular voltage pulse using subsequent negative stroke current wave shape

Generally, for either a rectangular or realistic voltage wave shape, the correlation between break down voltages and time to break down can be described by the impulse voltage- time curve as shown in Figure 2 [13]. This curve can be found for each gap geometry by applying different peak values of voltage [14].

According to constant area criterion or voltage-time law, in a gap geometry the discharge takes place at time as Figure 3, if the area by which the applied voltage exceeds a reference voltage (reached at time) is equal to a critical value A. this critical value is assumed to be constant independent of the shape of the impulse, while the parameters A and depend on voltage polarity, electrode geometry and gap spacing [15, 16]. Therefore, for an impulse voltage equation (2) can be derived.

The parameters of equation (2) are shown in Figure 3. The static voltage U_0 (kV) in equation (2) is the threshold below which no flashover occurs. Also, U_0 is related to separation distance by equation (4), as well as A which is the voltage-time area of voltage wave shape and is related to separation distance by equation (3). The values of A derived from a large series of experiments on rod-rod gap. Note that equation (4) considers the negative rod-rod arrangement. Table I indicates other values of A for different types of gap arrangement [16].

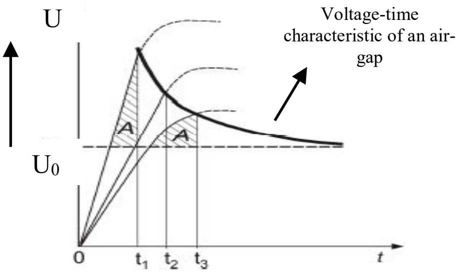

Fig. 2. The construction of voltage-time characteristic [14]

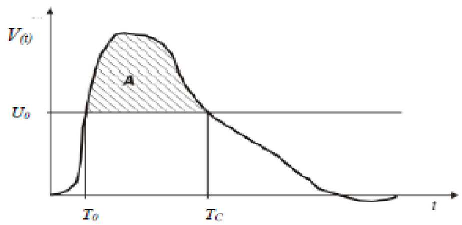

Fig. 3. Illustration of constant area criterion [7]

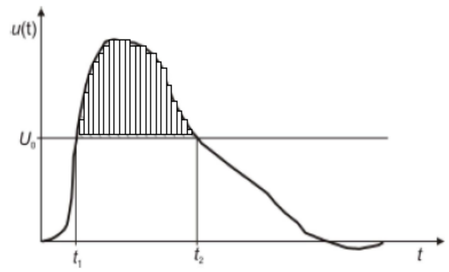

Fig. 4. Division of the area to finite sequence of partitions [17]

Fig. 5. VALUES OF A/S FOR DIFFERENT GAP ARRANGEMENT

Arrangement	A/s[kV.µs/m]
Positive rod – plane gap	650
Negative rod – plane gap	400
Positive rod – rod gap	620
Negative rod – rod gap	590

$$\int_{t_1}^{t_2}[u(t)-u_0].dt = A \qquad (2)$$

Where:

A is the voltage-time area of the voltage wave shape [kV.µs]

$$A = 590.s \quad [16] \quad (\text{kV.µs}) \qquad (3)$$

$$U_0 = \theta.s \quad [17] \quad (\text{kV}) \qquad (4)$$

Where:

$\boldsymbol{\theta}$=534 [7]

U_0 is the static break down voltage [kV]

S is the flashover distance [m]

A is the voltage-time area of voltage wave shape [kV. µs]

In this study, the rod-rod geometry is used as basis for the calculation because the rod-rod gap geometry is closer to practical arrangements. Also, the rod-rod gap geometry is the worst case scenario (as the required minimum separation for rod-rod gap is more than that for any other geometry), so from the point of view of the protection against flashovers it is safe due to higher value of flashover distance. The induced voltage across the gap due to flowing of lightning current in the LPS of a building is calculated by applying the node-potential analysis. According to the constant area criterion, the voltage-time area of the induced voltage wave shape A is considered to be the whole area above U_0 as it is shown in Figure 3 which makes sure that after T_C no break down will occur. In Sowa's study [13], the voltage-time area (A) has been approximated by rectangle, trapezium and triangle shape.

In this study, in order to calculate the separation distance more accurately, the voltage-time area of the voltage wave shape is calculated by numerical integration method[17]. By numerical integration method, the time interval (t_1, t_2) of the voltage wave shape as shown in Figure 4 is divided to a finite sequence of numbers of the form:

$$t_1 = x_0 < x_1 < \cdots < x_n = t_2$$

Each (xi, xi+1) is called a subinterval. The norm of a partition is defined to be:

$$max(x_i - x_{i-1})\,, i \in (0, n-1)$$

The whole area is divided into partitions with these intervals as shown in Figure 4, while the tagged partition $p(x,t)$ of an interval, is a partition together with a finite sequence of numbers $t_0, \dots, t_{n-1}$ subject to the condition that for each i, $t_i \in (x_i\,, x_{i+1})$.

The area of all the rectangles can be calculated according to equation (5)

$$\text{A}= \sum_{i=0}^{n-1} f_{(t_i)(x_{i+1}-x_i)} \qquad (5)$$

Therefore, using equation (4),

$$\sum_{i=0}^{n-1} f_{(t_i)(x_{i+1}-x_i)} = 590.s \qquad (6)$$

$$s = \frac{\sum_{i=0}^{n-1} f_{(t_i)(x_{i+1}-x_i)}}{590} \qquad (7)$$

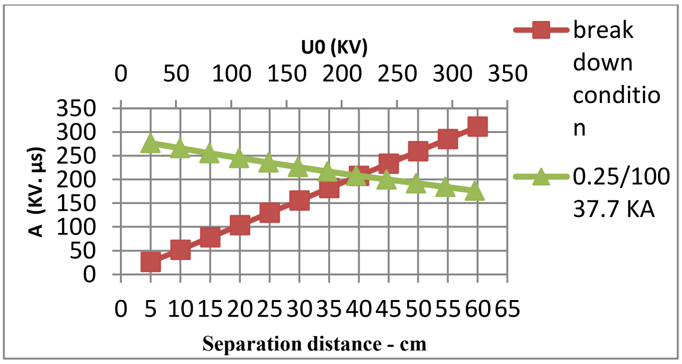

Fig. 6. Relation between integral *A*, static breakdown voltage U_0 and Separation distance *d*

In proposed method since the static break down voltage is dependent on the separation distance according to equation (4), the voltage-time area has been calculated by numerical integration method for different values of U_0. To obtain the separation distance, the results of voltage-time area versus the static break down voltage have been plotted while values of U_0 were linked to the values of separation distance as shown in Figure 5. By crossing the $A(U_0)$ with the curve representing equation (3) according to the equation (2), the value of separation distance can be obtained.

I. Development of Models in PSCAD

The study of current and voltage distributions in the LPS of a building was conducted by different numerical modelling approaches. These approaches can be classified in three categories, i.e. the equivalent circuit approach[18], the field approach [19] and the partial element equivalent circuit (PEEC) approach[20]. The mathematical model based on electric field integral equation describes the interaction between the conductive parts of the LPS. These models are useful when the effect of the LPS geometry on the electromagnetic field inside the building is required, or evaluation of electromagnetic interfaces due to indirect lightning strike is implemented[21]. However, in order to evaluate the interferences to circuits in the vicinity of the structure directly injected by lightning current, the radiation field can be neglected[22]. The important phenomenon in this scenario is the lightning current distribution along the various paths of the structure. Besides, in the practical cases of interest, the phenomenon can be considered as quasi-stationary. For these reasons a circuital approach which is used in this work, seems to be appropriate to simulate practical cases, especially when the structure can be reasonably approximated by a set of interconnected conductive branches [21, 22].

The equivalent circuit approach is a simple approach for modelling the building structure. In this approach, all the branches of conductors in building structure are divided into a number of elements considering the propagation phenomena. Each of these elements is modelled as a π-type circuit and coupled to other elements as can be seen in Figure 6.

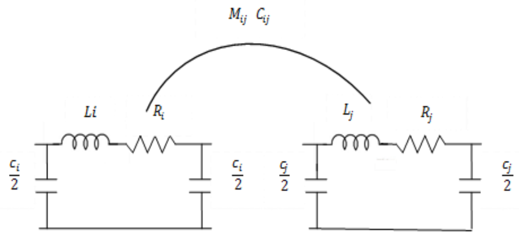

Fig. 7. Coupled π type circuit

By modeling the building to an equivalent electrical network, the assessment of node voltages and branch currents, either in time domain or frequency domain, can be conducted. Also, by having the voltages and induced current, electric field and magnetic field can be easily calculated[23]. In fact, each cylindrical conductor of the LPS divided into short segments with the length of each segment should be less than 1/10 of the wave length of the maximal frequency of lightning current in order to take into account the propagation phenomena of lightning discharge current over a long conductor[24]. Each section is modelled as a lumped π circuit with the impedance of the conductors is determined by its geometric parameters and material properties.

Besides the electrical network of the LPS, the lightning current is simulated as well. The lightning current basically consist of short strokes and long strokes with duration less than 2 ms and longer than 2 ms, respectively. The short strokes itself include negative first stroke, subsequent negative stroke and positive stroke [25]. In this study, only the short strokes are considered for simulation of lightning current. This assumption was done due to the negligible peak amplitude of long stroke current I_p and small value of peak current derivative $(\frac{di}{dt})$.

The peak value of lightning current and current derivative is directly related to the potential rise at strike point. The potential of strike point as it is shown in Figure 7 is equal to the potential across the resistance and inductance of the LPS conductor according to equation (8). The potential across the R and L depends on the value of current and derivative of the current which flows through R and L and is named in Figure 8 as I, and can be calculated according to equation (9). The term It in equation (9) which is the total lightning current which flows through the conductor divides into two parts, i.e. the current of the capacitance and the conductance I', and the current which flows through the resistance and inductance I. The I' current itself is divided into the capacitance current IC and the conductance current IG as it is substituted in equation (10). Where, the value of IC can be calculated according to equation (11), in which the capacitance is a very small value that is almost 10^{-15}F, and the voltage derivative is some kilo volts per micro second, which makes the IC a very small value, i.e. around 10^{-6} A. Besides IC, IG which can be calculated according to equation (30), is the current that flows through the resistance of a specified column of air in between the conductor and the earth which has a very small conductance, i.e. almost equal to $10^{-15}\ \Omega^{-1}$, which makes the I_G a very small value, i.e. around 10^{-12}A. Therefore, the I' current is remarkably small value and in comparison with the total lightning current which is some ten kilo volts, can be neglected. By substituting I_C and I_G in equation (10) with equation (11) and (12), the potential of strike point which is shown by equation (8) is rewritten as equation (13), whereas the values of I_C and I_G are negligible. Therefore, equation (13) can be simplified and rewritten as equation (14).

In the simulated circuit, the lightning current stroke was modelled as an impulse current source. IEC62305-1 Standard defined three wave shapes for positive, subsequent negative and first negative strokes which are 10/350µs, 0.25/100 µs and 1/200 µs, respectively and have been defined with Heidler function in standard IEC62305-1 Standard [25]. In this research, the Heidler function which is presented in 1985[26] has been carried out for the mathematical model of lightning current. This function has been defined as equation (15), where I - peak current [kA], k - correction factor for the peak current, t - time [s], τ_1 - front time constant [µs] and τ_2 - tail time constant [µs].

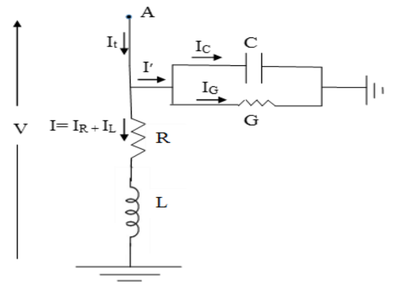

Fig. 8. Lightning current division in the R, L, C and G parameters of LPS

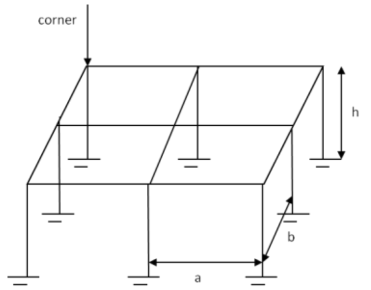

Fig. 9. 20 m × 20 m × 20 m dimension structure of LPS: a=b=20 m, h=20

$$v = RI_p + L\left(\frac{dI}{dt}\right)_p \quad (8)$$

$$I = I_t - Í \quad (9)$$

$$I = I_t - (I_c + I_G) \quad (10)$$

$$I_c = C.\frac{dV}{dt} \quad (11)$$

$$I_G = G.V \quad (12)$$

$$v = R.(I_t - C.\frac{dV}{dt} - G.V)_p + L.\left(\frac{d\left(I_t - C.\frac{dV}{dt} - G.V\right)}{dt}\right)_p \quad (13)$$

$$v = R.(I_t)_p + L\left(\frac{dI_t}{dt}\right)_p \quad (14)$$

$$i = \frac{I}{k}.\frac{(t/\tau_1)^{10}}{1+(t/\tau_1)^{10}}.exp\,(-t/\tau_2) \quad (15)$$

IV. RESULTS

The results of separation distance strongly depend on the LPS analyzed, lightning stroke location, the grounding system configuration and soil parameters as well as lightning current wave shape and its parameters. In this study, a building with the LPS dimension of 20 m × 20 m × 20 m has been carried out as illustrated in Figure 8. This building is protected by a mesh type air termination system with 10 m × 10 m mesh size which is connected to the down conductors and to the earthing electrodes. In this building the conductors of the LPS have 4 mm radius. Also, the ground is assumed to be perfect and considered as zero potential. While, all metallic components on the roof are connected to the same earthing system of the building which is a common practice according to IEC62305-3 standard. Therefore, the voltage across the gap between the LPS and metallic components can be determined by measuring the potential of strike point on the LPS to the remote ground.

Results are calculated by PSCAD for a corner strike of negative subsequent stroke to the building. In calculations, the subsequent negative stroke was represented by a lumped current source, the source surge current of 37.5 kA peak value and 0.25/100 μs wave shape was simulated. The source current was described using equation (15).

Simulated results of separation distance is indicated in TABLE II for three assumed voltage wave shape of rectangle, triangle, trapezium and the real voltage wave shape. The simulated results also compared with the simulated results calculated in EMTP by Sowa [13]. It can be seen that the results for assumed non-real voltage wave shapes developed in PSCAD are in good agreement with the EMTP results obtained by Sowa.

It is illustrated that the value of separation distance calculated by considering the real voltage wave shape is lower than other three assumed voltage wave shapes. This difference is due to the overestimation in calculation of the area of voltage-time by considering this area as rectangle, trapezium and triangle. In all these three assumption the real voltage wave shape is surrounded by these shapes which make the separation distance a higher value. The value of the separation distance is more accurate by calculating the area by numerical integration method. Indeed, the result of separation distance calculated by IEC62305-3 Standard formula that is addressed by equation (2) is shown in the last row of Table II. It can be seen that the calculated separation distance by proposed method is almost 19 % lower than the value calculated by IEC62305-3 Standard formula. It can be concluded that the IEC suggested formula in comparison with the values obtained by proposed method overestimate the value of the separation distance.

TABLE I. SEPARATION DISTANCE FOR 20 M × 20 M × 20 M LPS STRUCTURE IN CASE OF CORNER STRIKE

	Separation Distance (cm)	
Calculation based on	***Computation using PSCAD***	***Computation in EMTP by Sowa. A (2010)***
Rectangle Voltage wave shape	95.5	96.25
Triangle Voltage wave shape	49.5	49.13
Trapezium Voltage wave shape	64	61.41
Proposed method (Real voltage wave shape)	31	…….
IEC62305-3 standard equation	38.2	38.88

Moreover, by computing the required distance for the building in Figure 9 but with different length of down conductors, a set of results can be generated to show the effect of length of down conductor on separation distance as indicated in Table III. According to these results, the difference between the Values of separation distance obtained by proposed method and IEC method are more obvious by increasing the length of down conductors. This difference is almost 20% when the length of down conductor is 60m.

Indeed, the higher the length of the down conductor, the higher is the separation distance. In fact, by increasing the length of down conductors the potential across the gap increases leading to a higher separation distance. Same trends have been recorded for separation distance by IEC method.

TABLE II. SEPARATION DISTANCES FOR 20 M × 20 M BASED CONFIGURATION OF LPS WITH DIFFERENT LENGTH OF DOWN CONDUCTORS

Length of down conductors (m)	Voltage across the gap (MV)	Separation distance-IEC method (cm)	Separation distance - proposed method (cm)
10	**0.904**	**26**	**21**
20	**1.329**	**38.2**	**31**
40	**1.837**	**52**	**41**
60	**2.548**	**73**	**58**

Furthermore, the results of separation distance by proposed method have been obtained for different amplitude of subsequent short stroke lightning current injected to the corner down conductor of the same LPS as shown in Figure 9 and same scenario. Results of Table III indicate that by increasing the lightning current amplitude, the value of separation distance increases as the voltage across the gap increases. According to the results of Table III, by increasing the amplitude of subsequent negative stroke lightning current by 25 kA, the voltage across the gap increases for almost 888 kV.

TABLE III. SEPARATION DISTANCE AND VOLTAGE ACROSS THE GAP CALCULATED BY PROPOSED METHOD FOR DIFFERENT AMPLITUDE OF SUBSEQUENT SHORT STROKE LIGHTNING CURRENT

Lightning current amplitude (kA)	Voltage across the gap (kV)	separation distance (cm)
25	887.7	20
50	1775.8	39
75	2662.8	59
100	3551.6	80

II. PARAMETERS INFLUENCE THE VALUE OF THE SEPARATION DISTANCE

Results of the last section were calculated considering the subsequent negative stroke injected to the corner of the LPS. In this section two other components of short stroke are determined and the values of separation distances are calculated. Therefore, by considering the positive stroke and first negative stroke for lightning current and comparing the results of these three short strokes, the worst scenario where the separation distance value is the highest value can be discovered.

For this purpose, the subsequent negative stroke, first negative stroke and positive stroke have been simulated based on the defined wave shapes in IEC62305-1 Standard as 0.25/100 µs, 1/200 µs and 10/350 µs, respectively.
In calculations, the short stroke was represented by a lumped current source, the source surge current of 50 kA peak value with the above wave shapes. The source current wave was described using equation (15). The parameter in this equation have been defined in IEC62305-1 for three wave shapes of 0.25/100 µs, 1/200 µs and 10/350 µs.

Table IV shows the results of separation distance for the building with the LPS configuration of Figure 9, in case of a corner strike of short stroke lightning current to the building. The ground is assumed to be perfect (R=0).

The results in Table IV illustrate a significant difference in the value of separation distance for three wave shapes. While, the highest value of separation distance belongs to the subsequent negative stroke with 39 cm, and the lowest value is related to the positive stroke with 6 cm. In fact by increasing the front time of the lightning current wave shape from 0.25 µs to 1 µs and 10 µs, the value of separation distance decreases from 39 cm to 26 cm and 6.1 cm, respectively. Therefore, it can be concluded that the results of separation distance for subsequent negative stroke which have been calculated in last section determines the worst case scenario.

TABLE IV. SEPARATION DISTANCE FOR THREE COMPONENTS OF SHORT STROKE LIGHTNING CURRENT PRESCRIBED IN IEC62305-1

Lightning current Wave shape (kA)	Voltage across the gap (kV)	separation distance (cm)
0.25/100 µs subsequent negative stroke	1775.8	39
1/200 µs first negative stroke	444.8	26
10/350 µs positive stroke	43.55	6.1

The simulated results of Table IV have been repeated for different amplitude of lightning current. The results are illustrated in Figure 9. It can be seen from the results that by increasing the lightning current amplitude, the separation distance increases but this increment is different for these three short strokes. The most increment has been observed for the subsequent negative stroke and the least increment belongs to the positive stroke.

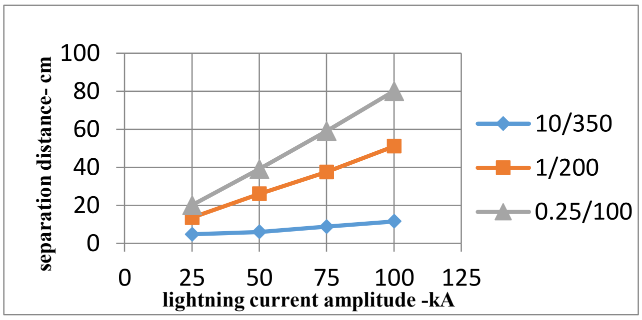

Fig. 10. : Relation between separation distance and peak value of lightning current

Furthermore, in this section the effect of earth resistance on the value of separation distance has been evaluated. The short strokes lightning current have been injected to the corner of the LPS that is shown in Figure 9, While, each down conductor is connected to an earth rod. The earth rods have been modelled by distributed parameters as shown in Figure 7. In this model, values of inductance and capacitance have been assumed to be constant while the resistance varies from zero to ten ohm.

It can be observed in Table V that increasing the earth resistivity leads to increment in the value of separation distance. Indeed, it can be observed from the results that by changing the resistance from zero to 10 ohm, the separation distance varies from 6.1 to 13.2 cm for positive stroke, 26 to 30 cm for first negative stroke and 39 to 42 for subsequent negative stroke. Thus the most variation is related to the positive stroke.

As it has been explained, the voltage across the gap is dependent on peak value of current $(I)_p$ and peak value of current derivative$\left(\frac{di}{dt}\right)_p$. For subsequent negative stroke, the peak value of current derivative has a significant value. Therefore, by changing the resistance in equation (8) ($v = Ri_p + L\left(\frac{di}{dt}\right)_p$), the voltage across the gap changes only for some ten kilo volts which is a small amount in comparison to the total voltage across the gap (Mega volt). Therefore, the separation distance only changes for 3 cm when the resistance varies from zero to 10 ohm.

On the other hand, for positive stroke, the current derivative has lower value in comparison with the subsequent negative stroke. It can be seen that the separation distance for 10-ohm resistance is more than twice of the value for zero resistance. It shows that because of the low value of current derivative for positive stroke the second part of equation (8) has a low value which makes the resistance in the first part of equation (8) an effective parameter when it is multiplied by current. In fact, the earth resistivity is an important parameter when the positive stroke is injected to the LPS.

TABLE V. SEPARATION DISTANCE AND VOLTAGE ACROSS THE GAP FOR 4 DIFFERENT EARTHING RESISTANCES WHEN THREE DIFFERENT LIGHTNIG WAVE SHAPES HAVE BEEN INJECTED TO THE LPS

Lightning Wave form	Rg (Ω)	Voltage across the gap (kV)	Separation distance (cm)
Positive Stroke	**0**	43.4	6.1
	0.5	45.5	6.2
	5	64.19	9.3
	10	89.8	13.2
First Negative Stroke	**0**	444.8	26
	0.5	446.8	26.5
	5	464.8	28
	10	484.8	30
Subsequent Negative Stroke	**0**	**1775.8**	**39**
	0.5	**1777.6**	**39**
	5	**1796.4**	**40.5**
	10	**1817.3**	**42**

Moreover, to assess the effect of inductance of the earth rods on the value of separation distance, the values of separation distance have been computed for different earth inductance, While, values of resistance and capacitance are constant. Table VI shows the results of separation distances for subsequent negative stroke, first negative stroke and positive stroke, respectively.

It can be observed from the results that by changing the inductance from zero to 18 μH, the value of separation distance changes from 39 to 57.5 cm, 26 to 37 cm and 6.1 to 8.5 cm for subsequent negative stroke, first negative stroke and positive stroke, respectively. Therefore, the most variation belongs to the subsequent negative stroke with the highest value of current derivative while the positive stroke has the lowest variation due to the lowest value of current derivative.

TABLE VI. SEPARATION DISTANCE AND VOLTAGE ACROSS THE GAP FOR 4 DIFFERENT EARTH INDUCTANCE WHEN THREE DIFFERENT LIGHTNING WAVE SHAPES HAVE BEEN INJECTED TO THE LPS

Lightning Wave Form	L(μH)	Voltage across the gap (kV)	Separation distance (cm)
Subsequent Negative Stroke	**0**	1775.8	39
	4.5	1987.4	43
	9	2185.8	46.8
	18	2558.4	57.5
Negative Stroke	**0**	**444.8**	**26**
	4.5	**497.8**	**28.7**
	9	**547.5**	**31.5**
	18	**640.8**	**37**
Positive Stroke	**0**	**43.4**	**6.1**
	4.5	**48.6**	**6.6**
	9	**53.4**	**7.2**
	18	**62.6**	**8.5**

Overall, we show in this study that at roof top level of a building the estimation of the separation distance depends on various electrical and physical parameters of both the LPS and the electrical systems installed. In space-restricted buildings in the modern world it is a challenging task to optimize the roof level components to lower the cost, enhance the aesthetic appearance and maximize space utility while giving serious concern on the protection and safety. Under such conditions under-protection or over-protection may severely handicap the building designers. The situation can be worse with problematic soil conditions that demand high cost for reducing the earth resistance [27, 28], otherwise imposing extremely dangerous potential gradients along the conductors. Sometimes, materials used for ground conditioning, such as bentonite may dust-off depositing fine conducting particles even at the roof level reducing the breakdown strength of media between the conducting parts [29, 30]. In such situations, it is the responsibility of the lightning protection system developer to optimize the space of safety between LPS and other components. This paper provides information with high significance for such computation.

V. CONCLUSIONs

Several conclusions were made in this study with regard to the separation distance. By the proposed method, the volt-time area of the voltage across the gap has been calculated by considering the real voltage wave shape. Therefore, the amplitude and shape of the voltage across the gap may vary by applying different amplitude of three types of short stroke lightning current.

Indeed, a comparison between the three types of short stroke which are specified with three standard wave shapes in IEC62305-1 Standard. it has been proved that the worst scenario belongs to the subsequent negative stroke lightning current and the lowest separation distance belongs to the positive stroke.

Besides the parameters of the lightning current, other parameters in the LPS of the building have been considered, i.e. the length of the down conductor, the earth resistance and earth inductance. Results indicates that increasing the earth resistance when other parameters are constant leads to higher separation distance, as well as earth inductance. Same results have been observed by increasing the length of down conductors.

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