# The technical and economic assessment of the lightning rod symmetrization effect on overvoltage in narrow structures.

Jan Mikeš, Marcela Efmertová and Jiří Kutáč

***Abstract*—The authors of the article accentuate the significance of symmetrical placement of lightning conductors on the position of lightning current in them. The aim of the article is to prove the instructions described in the standard IEC 62305 and confirm the conclusion that buildings should be protected not only by a lightning rod but also by lightning conductors that constitute an irreplaceable component of a comprehensive protection system. If lightning rod influences the safe placement of lightning discharge above a building, then individual lightning conductor determines its safe grounding.**

**Lightning conductors have a major impact on the induction of lightning current in structures. Unfortunately, many buildings whose height is much bigger than their width (towers, lookout towers, high-rise buildings, factory stacks) contain only one lightning conductor, which does not ensure their protection.**

**The authors prove this fact on examples of protection of structures such as lookout towers and wind power plants.**

***Keywords*—lightning, lightning rod, symmetrization, EMC, IEC 62305.**

## I. Introduction

The external lightning protection system (LPS) is intended to intercept direct lightning flashes to the structure, including flashes to its side, and to conduct the lightning current from the point of strike to the ground. The external LPS is also intended to disperse this current into the earth without causing thermal or mechanical damage, or dangerous sparking which may trigger fire or explosions [8].

These conclusions, which were drawn at the end of 19th and the beginning of 20th century, are compared with the Rolling Sphere Method and the Protective Angle Method, based on the IEC 62305 standard, and now with a mathematical model. Not all high-rise structures are known to comply with this particular requirement. The authors trace the distribution of lightning currents in down-conductors and the influence of the electromagnetic field penetrating into the interior of the building.

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The main aim of this article is to point out that symmetrical placement of lightning rods is neglected which results in insufficient protection of structures. The proof of insufficient protection by a single lightning rod and its consequences is shown on our computer model.

There are several well-founded specialized studies dealing with induced overvoltage and overcurrent from direct and indirect flash current strikes [1-6]. However, the authors of the article sought the path of finding a simple practical tool that would help primarily practical electricians and designers of external lightning protection systems in deciding about their choice and application.

## II. Historical context

In Prague (Czech Republic), symmetrical lightning conductors were studied by Karel Václav Emanuel Zenger (1830-1908), professor of physics at the Czech Technical University at the beginning of the 1870s. A report on the influence of symmetrically-placed conductors was presented not only in Prague at the Czech Royal Society of Science in 1872 but it was also sent to many well-known European academies (Paris, London, Edinburgh, Brussels). Zenger´s conclusions were also endorsed by Sir W. Thomson. Karel Václav Zenger carried on the research performed by Václav Prokop Diviš (1698-1765), the first specialist of this kind in the Czech lands who was studying lightning rod at the same time as the American scientist Benjamin Franklin (1706-1790). Zenger introduced his findings at the First Electrotechnical Congress in Paris in 1881.

Two years later (1883) he suggested the use of an ‘ovoid’, a special lightning rod ending of an elliptical shape. Karel Václav Zenger was also the first physicist who suggested protection of town buildings by symmetrically placed lightning rods. Consequently, he managed to protect many public buildings in Prague such as the Czech Technical University in Karlovo náměstí (Charles Square), comprehensive high school in Ječná Street, the newly reconstructed National Theater and the Petřín Lookout Tower.

The Zenger lightning rods were produced by the Deckert and Homolka company. Karel Václav Zenger played a similar role as the Belgian scientist Louis Hénri F. Melsens (1814-1886), who put a similar lightning rod on the 91m-high Brussels town hall in 1865, and the Englishman James C. Maxwell (1831-1879) or the French structural engineer and architect Gustav Eiffel (1832-1923) who placed his lightning rod on his well-known tower. Zenger´s lightning rod was an ingenuous simplification of the Faraday cage. His lightning rod was widely used in the Austro-Hungarian Empire, Germany, Serbia and in Bulgaria. It has been used to this day. The authors put Zenger's findings in contrast with contemporary views on the theories of building protection.

## III. GOALS OF THE WORK

As regards lightning protection, the IEC 62305 standard recommends for each structure a greater number of parallel down-conductors, but this condition is not always met. Just one down-conductor ending in grounding is very often installed in high-rise - primarily technological - structures (lookout towers, wind power plants, technological masts).

Another very frequent negative phenomenon in the installation of external lightning protection systems is underestimation of the separation distance in high-rise structures in all parts of the object under scrutiny. There are theories which are based on gradual reduction of the amplitude of the advancing wave of lightning current with the decreasing height of down-conductor and which allow for the reduction of its size in the lower sections of the structure. Using a mathematical model, the authors of this article prove dependence of the separation distance on the distance from the point of strike of the down-conductor as far as grounding, demonstrating the actual lightning current distribution along the down-conductor.

## IV. THE THEORETICAL BACKGROUND

Objects struck by lightning are subject to higher stress by downward flashes (cloud to earth) than by upward flashes (earth to cloud). Depending on the type of lightning flash, each lightning discharge consists of one or more partial strikes of lightning. Features of partial lightning strikes are their polarity (negative, positive) and their temporal position in the lightning discharge (first, subsequent or superimposed partial discharge). The important parameters for lightning protection systems are as follows:

Peak value of lightning current ($I_{max}$), charge of lightning current (Q), specific energy (W/R) and steepness (di/dt) [7].

It is important for primary modeling of lightning current to know the actual lightning protection level and then the maximum of lightning current.

TABLE I
WAVEFORM 10/350 µs

| *Wave* | *LPS – lightning protection level* | *Maximum lightning current peak value [kA]* | *Probability of actually lightning current to be less than maximum* | *Coefficient $k_i$ [-]* |
|---|---|---|---|---|
| *10/350 µs* | I | 200 | 99 % | 0.08 |
| | II | 150 | 98 % | 0.06 |
| | III+IV | 100 | 97 % | 0.04 |

Heidler´s function was used for analytical modeling of lightning current [9].

$$i = \frac{i_{max}}{\eta} \cdot \frac{\left(\frac{1}{T}\right)^{10}}{1+\left(\frac{1}{T}\right)^{10}} \cdot e^{-\frac{t}{\tau}}, \text{[A]} \quad (1)$$

TABLE II
PARAMETERS OF ANALYTICAL FUNCTION 10/350 µs

| *Current wave T1/T2* | |
|---|---|
| *10/350 µs* | |
| ***η*** | 0.93 |
| ***T*** | 19.0 µs |
| ***τ*** | 485 µs |

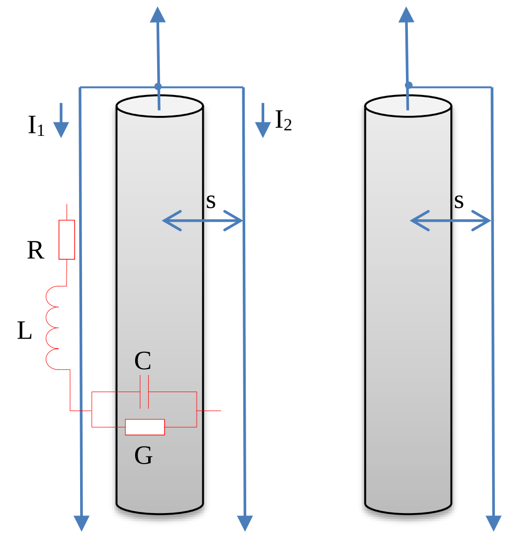


Fig. 1. Symmetrical and asymmetrical down-conductors.

Electrical insulation between the air-termination or the down-conductor and the structural metal parts, the metal installations and the internal systems can be achieved by providing a separation distance, ***s***, between the parts. The general equation for the calculation of ***s*** is given by [8]:

$$s = \frac{k_i}{k_m} k_c l, \quad \text{[m]} \quad (2)$$

where:

$k_i$ depends on the selected class of LPS

$k_m$ depends on the electrical insulation material

$k_c$ depends on the (partial) lightning current flowing on the air-termination and the down-conductor

$l$ is the length, in meters, along the air-termination and the down-conductor from the point, where the separation distance is to be considered, to the nearest equipotential bonding point or the earth termination.

In order to reduce the probability of damage due to lightning current flowing in the LPS, down-conductors shall be arranged in such a way that from the point of strike to earth [8]:

a) several parallel current paths exist;

b) the length of the current paths is kept to a minimum

## V. Mathematical model

The mathematical model of the lightning conductor is composed of an ideal model of transmission line supplemented by real parameters of resistance, self- and, mutual-inductance, capacitance and conduction inside the building. These parameters were based on precise calculations on the material. This model was adopted from the papers presented at the ICLP 2014 conference [11]. Based on the input data, a numerical model was designed by the computer program Matlab R 2013a and improved for this purpose.

## VI. Description of two lightning conductors

$$\frac{\partial^2 i_1(x,t)}{\partial x^2} = L_1 C \frac{\partial^2 i_1(x,t)}{\partial t^2} + L_1 G \frac{\partial i_1(x,t)}{\partial t} + MC \frac{\partial^2 i_2(x,t)}{\partial t^2} + MG \frac{\partial i_2(x,t)}{\partial t} + R_1 C \frac{\partial i_1(x,t)}{\partial t} + R_1 \cdot G \cdot i_1(x,t) \tag{3}$$

$$\frac{\partial^2 i_2(x,t)}{\partial x^2} = L_2 C \frac{\partial^2 i_2(x,t)}{\partial t^2} + L_2 G \frac{\partial i_2(x,t)}{\partial t} + MC \frac{\partial^2 i_1(x,t)}{\partial t^2} + MG \frac{\partial i_1(x,t)}{\partial t} + R_2 C \frac{\partial i_2(x,t)}{\partial t} + R_2 \cdot G \cdot i_2(x,t) \tag{4}$$

The final system can be written for current in the form:

$$\frac{\partial^2}{\partial x^2}\begin{bmatrix} i_1(x,t) \\ i_2(x,t) \end{bmatrix} - C \cdot \frac{\partial^2}{\partial t^2}\begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \cdot \begin{bmatrix} i_1(x,t) \\ i_2(x,t) \end{bmatrix} - \frac{\partial}{\partial t}\begin{bmatrix} L_1 G + R_1 C & MG \\ MG & L_2 G + R_2 C \end{bmatrix} \cdot \begin{bmatrix} i_1(x,t) \\ i_2(x,t) \end{bmatrix} - G \cdot \begin{bmatrix} R_1 \\ R_2 \end{bmatrix} \cdot \begin{bmatrix} i_1(x,t) \\ i_2(x,t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{5}$$

## VII. Numerical approach

For the solution of the hyperbolic partial differential equation (5) we used the Lax-Wendroff second order accurate method [10]. The problem is described in $(\mathbf{0}, \boldsymbol{T}) \times (\mathbf{0}, \boldsymbol{D})$, where $\boldsymbol{M}, \boldsymbol{L}, \boldsymbol{C}, \boldsymbol{G}, \boldsymbol{R}$ are constants and $\boldsymbol{I}(\boldsymbol{t}, \boldsymbol{x}) = \begin{bmatrix} \boldsymbol{i_1}(\boldsymbol{t}, \boldsymbol{x}) \\ \boldsymbol{i_2}(\boldsymbol{t}, \boldsymbol{x}) \end{bmatrix}$: $(\mathbf{0}, \boldsymbol{T}) \times (\mathbf{0}, \boldsymbol{D}) \to \mathbb{R}^2$ is an unknown current function. The approximations have to be complemented by the Dirichlet´s boundary conditions: $\boldsymbol{I}(\boldsymbol{t}, \mathbf{0}) = \boldsymbol{I_0}(\boldsymbol{t})$, in $(\mathbf{0}, \boldsymbol{T})$ and $\boldsymbol{I}(\boldsymbol{t}, \boldsymbol{D}) = \mathbf{0}$ in $(\mathbf{0}, \boldsymbol{T})$, where $\boldsymbol{I_0}$ represents the input impulse and boundary condition $\boldsymbol{I}(\boldsymbol{t}, \boldsymbol{D}) = \mathbf{0}$ is due to the grounding conductor, and using the initial conditions $\boldsymbol{I}(\mathbf{0}, \boldsymbol{x}) = \frac{\partial}{\partial t}\boldsymbol{I}(\mathbf{0}, \boldsymbol{x}) = \mathbf{0}$, in $(\mathbf{0}, \boldsymbol{D})$.

We replace the continuous domain by a uniform grid with space and time steps $\boldsymbol{h} > \mathbf{0}$ and $\boldsymbol{\tau} > \mathbf{0}$, respectively, of the computational domain. Let $\boldsymbol{x_k} = \boldsymbol{kh}$, $\boldsymbol{k} = \mathbf{0}, \dots \dots, \boldsymbol{N}$, the space nodes and $\boldsymbol{t_l} = \boldsymbol{l\tau}$, $\boldsymbol{l} = \mathbf{0}, \dots \dots, \boldsymbol{M}$, the times nodes. We denote the approximation $\boldsymbol{I_k^l} \equiv \boldsymbol{I}(\boldsymbol{t_l}, \boldsymbol{x_k})$ as the current in the discretization nodes. The finite difference approximation at $(\boldsymbol{t_l}, \boldsymbol{x_k})$ using the Lax-Wendroff second order method reads:

$$I_k^l \approx \frac{1}{4} \cdot \left[I_k^{l-1} + I_{k+1}^{l-1} + I_k^l + I_{k+1}^l\right] \tag{6}$$

$$\frac{\partial}{\partial t} I_k^l \approx \frac{1}{2} \cdot \left[\frac{I_k^l - I_k^{l-1}}{\tau} + \frac{I_{k+1}^l - I_{k+1}^{l-1}}{\tau}\right] \tag{7}$$

$$\frac{\partial^2}{\partial t^2} I_k^l \approx \frac{1}{4} \cdot \left[\frac{I_k^l - 2 \cdot I_k^{l-1} + I_k^{l-2}}{\tau^2} + 2 \cdot \frac{I_{k+1}^l - 2 \cdot I_{k+1}^{l-1} + I_{k+1}^{l-2}}{\tau^2} + \frac{I_{k+2}^l - 2 \cdot I_{k+2}^{l-1} + I_{k+2}^{l-2}}{\tau^2}\right] \tag{8}$$

$$\frac{\partial^2}{\partial x^2} I_k^l \approx \frac{1}{4} \cdot \left[\frac{I_{k+2}^l - 2 \cdot I_{k+1}^l + I_k^l}{h^2} + 2 \cdot \frac{I_{k+2}^{l-1} - 2 \cdot I_{k+1}^{l-1} + I_k^{l-1}}{h^2} + \frac{I_{k+2}^{l-2} - 2 \cdot I_{k+1}^{l-2} + I_k^{l-2}}{h^2}\right] \tag{9}$$

where $k = 0, \dots \dots, N-2$ a $l = 2, \dots \dots, M$.

Inserting Lax-Wendroff approximations into (5), for each time level we obtain $\boldsymbol{k} = \mathbf{0}, \dots \dots, \boldsymbol{N} - \mathbf{2}$ and $\boldsymbol{l} = \mathbf{2}, \dots \dots, \boldsymbol{M}$ linear algebraic equations formally written in the form:

$$d_k^l \cdot I_k^l + d_{k+1}^l \cdot I_{k+1}^l + d_{k+2}^l \cdot I_{k+2}^l = F(I_k^{l-1}, I_{k+1}^{l-1}, I_{k+2}^{l-1}, I_k^{l-2}, I_{k+1}^{l-2}, I_{k+2}^{l-2}) \tag{10}$$

where $d_k^l, d_{k+1}^l d_{k+2}^l$ are matrix of coefficients and $F$ is a vector function of the previous time steps. We obtain a system of $M-2$ linear algebraic equations with $2(N-1)$ unknowns.

## VIII. Separation distance as a function of height of the structure

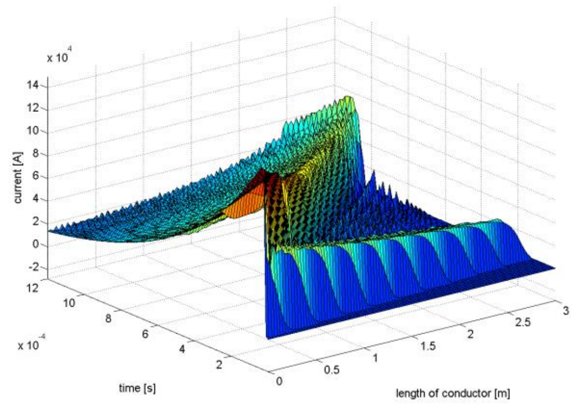


Fig. 2. Current distribution in one down-conductor of the length of 3 m when the input impulse 10/350 μs and $I_1$=150 kA.

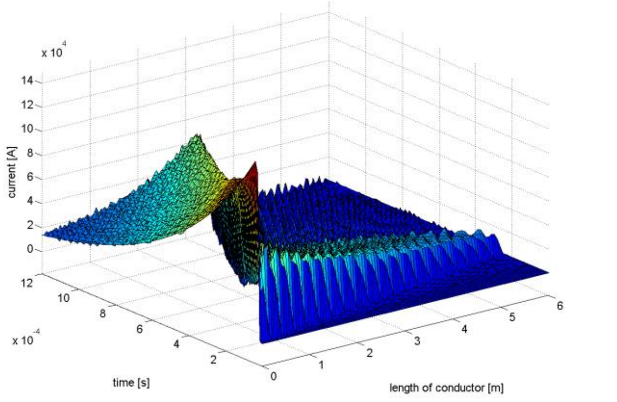


Fig. 3. Current distribution in one down-conductor of the length of 6 m when the input impulse 10/350 μs and $I_1$=150 kA.

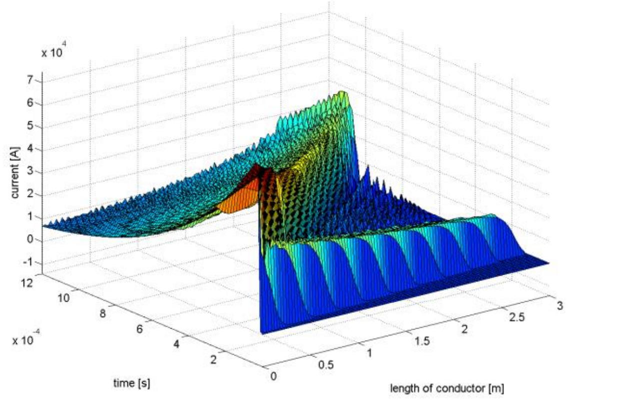


Fig. 5. Current distribution in one down-conductor of the length 3 m when the input impulse 10/350 μs and $I_1$=75 kA.

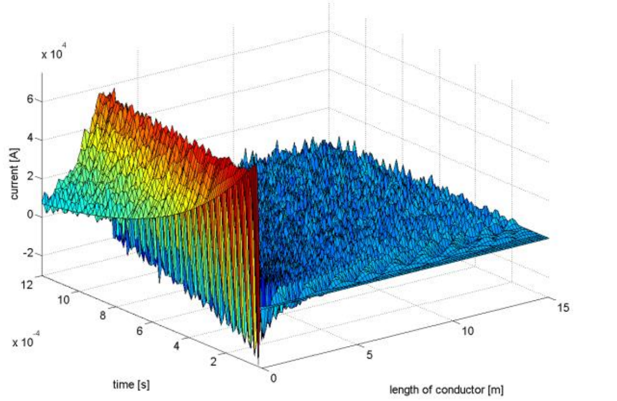


Fig. 4. Current distribution in one down-conductor of the length of 15 m when the input impulse 10/350 μs and $I_1$=150 kA.

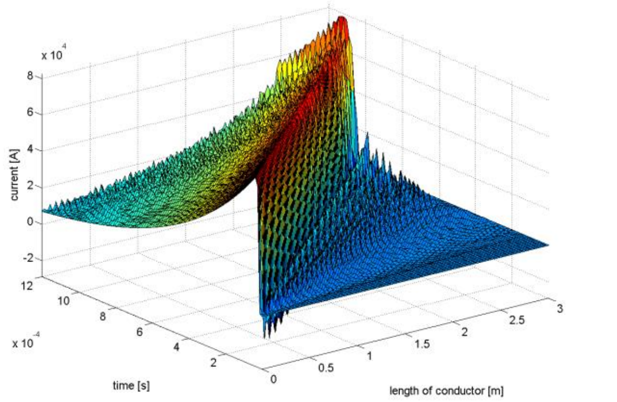


Fig. 6. Current distribution in both down-conductors of the length of 3 m when the input impulse 10/350 μs and $I_1$=75 kA.

Figs. 2-4 make it evident that the length of a down-conductor has a decisive impact on the reflected wave. With the decreasing length of down-conductor, the general rule may be proved that the separation distance between the inner electrical installation and the external lightning protection system may be implemented in lower parts of the structure by means of smaller values than in the position near the air-terminal. However, it is always vital to take into account the specific situation and configuration of the entire external lightning protection system. There may occur different C and L conditions during changes in climatic conditions and thus different capacitive and inductive couplings, and subsequently, also higher induced overvoltage.

Figs. 5-6 make it evident that in an electromagnetic coupling, mutual induced overvoltage in down-conductors may be higher at half the amplitude (division into two down-conductors) than the actual value corresponding to the passage of the same current through one down-conductor. Such phenomena may be extreme primarily in very narrow structures where down-conductors are situated close to one another.

## Conclusion

Using a mathematical model, the authors studied the significance of symmetrical lightning down-conductors for narrow high-rise structures. Proceeding from the IEC 62305 standard, they singled out one frequently neglected condition for the installation of symmetrical lightning down-conductors on high-rise structures. Installations are often made with one down-conductor, and in this way the condition imposed by the European standard is not met. The authors also trace the historical contexts of the emergence and use of symmetrical lightning protection systems not only in the Czech lands but also in the world.

The above charts ensuing from the model indicate that a major criterion in the assessment of the separation distance from the external lightning protection system is also the length of the down-conductor itself. In case of very small distances of down-conductors (in the order of units of meters), reflected lightning wave may prove to be so powerful that a high density of electrical current still remains in the down-conductor, thus threatening the inner installations by the lightning electromagnetic pulse (LEMP).

However, in many cases the capacitive and inductive coupling of down-conductors (primarily in extremely narrow structures) is so much important that oscillation and electromagnetic induction into both down-conductors may occur. In any case, it is suitable to check the specific given situation involving the installation of an external lightning protection system individually by designing and calculating an electromagnetic model and to calculate induced overvoltage into the object's inner installations.

## ACKNOWLEDGMENT

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