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Lightning Discharge Parameters in Building Lightning Protection Calculations

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Formation of the lightning discharge

Lightning protection theory was and is formed at the junction of sciences of high voltage equipment, geophysics and meteorology. For creation of efficient and rational lightning protection systems [1, 2] firstly it is necessary to know the physics of the lightning discharge process and its possible interaction with the object and the reaction of the object to the such impact. In order to assess this impact some certain lightning current parameters are required. Widely accepted mechanism of formation of negative polarity lightning discharge is discussed in references [3, 4]. When accumulated charges create a critical electrical field of 25 – 30 kV/cm in the environment of a could, the electron avalanches are initiated, which form plasma threads – streamers – in their lower part. Streamers in their turn connect with each other and cause the initial pulse of the discharge – leader, which spreads down to the ground. Average length of the streamers forming the bulk charge of the lightning leader is several tens of meters and can be calculated [5] :

$$l_{str} = \tau_{l\,\min} + k_{\tau} H_l \,/2\pi\varepsilon_0 E_{str}; \qquad (1)$$

here $\tau_{l\,\min}$ – initial bulk charge density of the leader; k_{τ} – coefficient related to the polarity of the discharge; H_l – leader channel length; E_{str} – average strength of the streamer field.

Leader moves in leaps and ionizes the air – creates the path for the primary discharge. It is practically impossible to foresee its movement trajectory in advance. Leader formes a hot ionized channel and its charges induce the charges of the opposite polarity at the surface of the ground. When the stair-shaped leader approaches the Earth surface, the concentration of the induced charges and the strength of the electrical field at the ground or at the heightened place increases and the leader of the opposite direction is formed, which moves from the highest points of the ground up to the stair-shaped leader. These two leaders by connecting with each other form the primary (lightning) discharge channel (this usually happens near the ground). So when the leader reaches the ground, the lightning itself begins from the surface of the Earth.

In this stage the charges are neutralized and a strong electric current flows through the channel which heats the channel up to 20 000 – 30 000 ^{0}C. Afterwards the second leader descends through the same channel (this time without any stops). Later discharge pulses taking place after the primary one usually emerge after 0.03 – 0.05 s; they already have suddenly formed leaders. There are usually from 2-3 to 10 repeated pulses of the discharge during 1 second. Sometimes the multiple lightning can have up to 40 or even more discharges which are repeated in periods from 500 μs to 0.5 s, and the duration of such lightning can last 1 s.

Average height of the thunderstorm clouds in Europe is close to 2-3 km and minimal is 600 m; therefore the length of the lightning current front may vary from $T_f = 600/3\cdot10^8 = 2\cdot10^{-6}$ s to $T_f = 3000/3\cdot10^8 = 10\cdot10^{-6}$ s.

By assessing the curvature of the spark channel the real minimal duration of the lightning current wave-front makes 2.5-5.0 μs, average – 7.0-15 μs. According to the recommendations of IEC (International Electrotechnical Commission) the duration of pulsed lightning wave-front is considered to be 10 μs (see Table 2).

As it is indicated in publication [5] the front length of the lightning current is characterized by the propagation duration of the electromagnetic wave along the leader channel and does not depend on the polarity of the discharge. Full duration of lightning current pulse is defined using the movement velocity of electrons emerging in the streamers during the neutralization of the leader bulk charge.

According to information presented by NLSI (National Lightning Safety Institute) approximately 40 % of lightnings hitting the ground multiply, i.e. two or more lightning channels reach the ground at the same time. It was also determined that the average safe distance between successive lightning discharges onto the ground is larger than it was considered earlier and has to be selected from the interval of 10 – 13 km, not from 2 – 5 km.

General lightning current parameters

Mechanical impact of the lightning current depends on the maximal current *I* and specific energy *W/R*. Thermal impact of the lightning depends on the specific energy *W/R* (in the closed contour with the resistance R) and the charge *Q* (electric arc is formed in the contour). Arcing is conditioned by the electromagnetic impact and it is proportional to the sharpness of the lightning current wavefront (di/dt).

In some cases, for example, in order to evaluate the thermal impact of the lightning channel on the object it is necessary to have not only the charge Q, but also the magnitude of the continuous lightning current component (DC). Stochastic values of the continuous lightning current component I_n are presented in the Fig. 1. Component I_n belongs to the currents which flow during the pauses between negative lightning pulses. The probabilities of the entire lightning current duration T_z and pauses T_p between negative lightning pulses are shown in Fig. 2 [4].

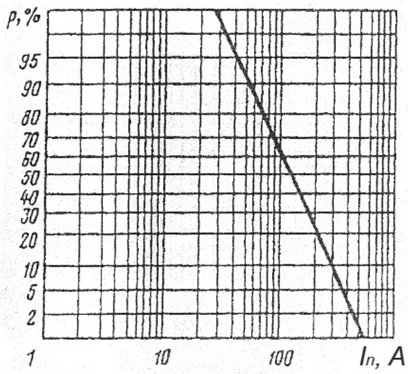

Fig. 1. Statistical data of the values of continuous lightning current component I_n

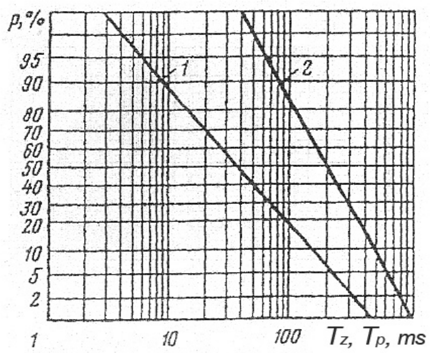

Fig. 2. Statistical data of the values of the entire lightning current duration T_z (2) and pauses T_p (1) between negative lightning pulses

All these parameters are not determined in unambiguous manner and have a probabilistic character. Many authors put efforts into their generalization with the aim to present general values for determination of the main current parameters (maximal current, sharpness of the wavefront, carried charge). Such generalization allows determining of the lightning current parameters when solving problems of the lightning safety and providing various objects with the lightning protection measures.

Table 1. Lightning parameters

Lightning parameters	Protection levels		
	I	II	III, IV
Maximum lightning pulse current *I*, kA	200	150	100
Full lightning charge Q_{Σ}, C	300	225	150
Pulse charge Q_{imp}, C	100	75	50
Specific energy *W/R*, kJ/Ω	10000	5600	2500
Average sharpness of the wavefront *di/dt* 30/90 %, kA/μs	200	75	50

Lightning parameters used in the lightning safety calculations are given in Tables 1-4; their use is recommended by the International Electrotechnical Commission. They reglament both the current amplitudes and the time parameters of the pulses. Lightning current parameters used for determination of the lightning safety system size are taken from the Table 1 depending on the level of the protection.

Table 2. Parameters of the initial lightning current pulse

Parameters of the current	Protection levels		
	I	II	III, IV
Maximum current *I*, kA	200	150	100
Lightning pulse wavefront duration T_1, μs	10	10	10
Decrease time of the lightning pulse wave current T_2, μs	350	350	350
Pulse charge Q_{Σ}*, C	100	75	50
Specific pulse energy *W/R***, MJ/Ω	10	5,6	2,5

* – maximum part of the entire charge Q_{Σ}, which is concentrated in the initial pulse; therefore it is assumed that the overall charge of all short pulses is equal to the indicated values.
** – largest part of all specific energy *W/R* concentrated in the initial pulse; therefore it is assumed that the overall energy of all pulses is equal to the indicated values.

Table 3. Parameters of the successive lightning current pulse

Parameters of the current	Protection levels		
	I	II	III, IV
Maximum current *I*, kA	50	37,5	25
Lightning pulse wavefront duration T_1, μs	0,25	0,25	0,25
Decrease time of the lightning pulse wave current T_2, μs	100	100	100
Average sharpness of the pulse current wavefront *a*, *kA/* μs	200	150	100

Table 4. Parameters of the long-term lightning current between the pulses

Parameters of the current	Protection levels		
	I	II	III, IV
Charge Q_t*, C	200	150	100
Duration *t*, s	0,5	0,5	0,5

When calculating distribution of the currents in the lightning safety system the lightning is considered as a current source, which initiates several pulses in the lightning safety system and other equipment related to it. This current induces electromagnetic noise, similarly as the current in the lightning channel. It is assumed at the same time, that the lightning current consists of the initial discharge of any polarity, successive discharge of negative polarity and long-term discharge of any polarity. Lightning current parameters at the discharge point assumed for different safety levels are presented in Tables 2–4.

When evaluating resistance of various equipment to the lightning discharge, lightning current shape description in analytical expression is required in addition to the quantitive amplitude-time characteristics of the lightning current pulse. In the lightning safety practice the biexponential current description model is used, which is verified by many experimental triggered measurements of the lightning current:

$$i(t) = \frac{I}{k} * \frac{(t/\tau_1)^{10}}{1+(t/\tau_1)^{10}} * \exp\left(-\frac{t}{\tau_2}\right); \qquad (2)$$

here I – maximal lightning current pulse value, kA; k – correction coefficient; t – time, µs; τ_1 – pulse front duration constant, µs (0,454 µs $\leq \tau_1 \leq$19 µs); τ_2 – pulse “tail” duration constant, µs (143 µs $\leq \tau_2 \leq$485 µs).

Values of the calculated parameters k, τ_1, τ_2, T_1 (calculated lightning current pulse front duration) and T_2 (calculated lightning current pulse duration) defined in the standard IEC 1312-1 are given in Table 5.

Table 5. Values of the calculated lightning pulse current parameters

Parameter	Initial pulse	Consecutive pulse
k	0,930	0,993
τ_1, µs	19	0,454
τ_2, µs	485	143
T_1, µs	10	0,25
T_2, µs	350	100

Tests of the object resistance to lightning currents induced by the thunderstorm discharges are carried out on the basis of IEC recommendations or the national standards. Two standard test pulses are provided in the normative documents – 1.2/50 µs (first number denotes the length of the pulse wavefront, second denotes the pulse length at the 0.5 level) and 8/20 µs.

Depending on the test object the amplitude of the 8/20 µs pulse may vary in wide range – from several kiloamperes to 150 – 200 kA. This pulse imitates not the lightning current but the current which is formed under the breakdown of the insulation, after actuation of the lightning arrester due to the surge, etc.

Lightning safety and lightning resistance tests can be carried out both in the real scale objects and also using the object models manufactured in some certain reduced scale. However as it is pointed in [6], the defined test pulses have very few similarities with the atmospheric surge shape. Thus the problem of the real resistance of the insulation is still discussed.

There are offerings related to the increase of the charge flowing through the test object and increase of the maximal current of the initial pulse. But at the present time with the rapid expansion of the application of semiconductor-based equipment more and more attention during the tests is given not to the power and thermal impacts, but to the frequency characteristics of the test current pulses [6]. Still there is scarce of statistical data related to the lightning current amplitude and pulse time parameters especially when it characterizes lightning discharges with maximal parameters.

In lightning safety practice some situations emerge which considerably differ from the calculated ones defined by various norms. In most cases their flow path can not be blocked, for example when lightning strikes the object (usually there are not many of them) and its weakly charged initial leaders can not initiate the returning streamer from the lightning arrester. In this case such lightning will strike the object even though under other circumstances the object could be considered as sufficiently protected against the lightning. Other reason of the lightning hit at the protected object – the lightning leader channel deviation from the vertical position in ten or more degrees.

As it is stated in the scientific publications [5], the maximal lightning current flows only then when all the streamers in the lightning channel participate in the current formation and therefore the current strength depends on the length of the leader channel, the discharge polarity and the channel grounding resistance. The sharpness of the lightning current wavefront is the other significant lightning safety parameter; it is defined using physical gas discharge constants (electron movement velocities in streamers, electromagnetic wave propagation velocities, the sum of strengths of the positive and negative electric field streamers), discharge polarity and spark channel grounding resistance.

Lightning safety experts say that the efficiency of the lightning protection device approximately by 90 % is determined by the proper installation of the lightning current grounding conductors and the presence of the grounding in the lightning arrester. For this reason we will consider how the object grounding impacts the lightning current strength and the sharpness of the wavefront. For this purpose we will apply the parallel between the lightning channel and vertically-charged conductor connection with the ground surface.

If the wire forms a short connection to the ground over some certain resistance, then the current amplitude in this wire can be calculated as

$$I_G = \sigma \cdot \upsilon \cdot \frac{Z}{Z + R_G}, \qquad (3)$$

here σ – charge density of the discharge; υ – wave propagation velocity; Z – wave resistance of the lightning channel; R_G – equivalent object grounding resistance.

If we mark the product $\sigma \cdot \upsilon$ as $I_{\max}$ and the right part of the formula divide by Z, then the lightning discharge current dependence on the equivalent object earthing resistance is obtained:

$$I(R_G) = I_{\max} / 1 + \frac{R_G}{Z}. \qquad (4)$$

Expression of the lightning current wavefront is obtained analogously:

$$a(R_G) = a(R_G = 0) / 1 + \frac{R_G}{Z}. \qquad (5)$$

Empiric dependence of lightning channel resistance Z on the amplitude of the current [6]:

$$Z = 140\left(1 + \frac{240}{I_{G,\max}}\right). \quad (6)$$

Presented formulas confirm the change of lightning current parameters subject to the resistance of the discharge channel and the specific ground resistance. The specific ground resistance in Lithuania vary from 10 Ωm to 7000 Ωm, therefore in the initial stage of the pulse the equivalent grounding resistance of the object may vary from 5 to 200 Ω and more depending on the soil type. Wave resistance of the lightning channel is considered to fall into the range of 1.1 – 8.0 kΩ, although theoretical research show that under the impact of significantly high lightning current values the wave resistance of the channel decreases down to 200 – 300 Ω. In this case if the object grounding resistance varies from 0 to 30 Ω and when the wave resistance of the object grounding is 200 Ω the change of the lightning current will amount up to 10 % and the wavefront sharpness will decrease 1.67 times compared to the case when the lightning discharge strikes the ground with a good soil conductivity. Lightning current flow duration will also increase 1.67 times. It follows from here that parameters of lightning current pulse in soil with high specific resistance may significantly differ from the statistical data. These factors and the returning leader are not considered in various lightning parameter calculation models. And there is no data related to the returning leader of the consecutive lightning current pulse at all. The price of such uncertainty is quite high. The selection of protection methods and measures depends on the source of the object damage. Unnecessary decrease or increase of the lightning current parameters may lead to the erroneous conclusion, which in turn may be related to substantial material losses.

Conclusions

Lightning impact magnitude is determined by many parameters – maximal lightning current amplitude, current wavefront duration, pulse duration, pecularities of current alternation over time, etc. As the analysis has shown, all these parameters can not be determined unambiguously and have a probablistical nature. Many authors attempt to generalize them and to present the general values. Such generalization allows to determine lightning current parameters when solving lightning protection problems and when providing various objects with lightning protection measures.

When assessing building resistance to the lightning strike, the distribution of lightning current amplitudes has to be corrected against the equivalent grounding resistance of the object. In most cases formula (2) is sufficient to perform modelling of lightning current. Analysis of literature sources demonstrated, that the more complex expression of the current is recommended to use when evaluating lightning resistance of the air lines.

After analysis of the current situation we suggest, that it is necessary to form a complex program of lightning safety research, which would span the research of the lightning and its impacts, the acquisition and analysis of the statistical data related to the thunderstorms, creation of new efficient methods and measures of protection against the lightning, which would also review the normative documents of lightning safety design and installation and form a new ones based on the modern scientific investigations and protection techniques.

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From the entire set of the electrical lightning parameters only the visible ones are the most significant. These are: maximal current amplitude, current wavefront duration, pulse duration, peculiarities of current alternations over time, etc. We suggest that this investigation could be useful when solving practical problems in the fields of design and installation of lightning protection measures in Lithuania. Ill. 2, bibl. 4 (in English; summaries in English, Russian and Lithuanian).

Н. Багданавичюс, А. Драбатюкас, Ш. Килюс. Параметры разряда молнии в расчетах молниезащиты зданий // Электроника и электротехника. – Каунас: Технология, 2009. – № 3(91). – С. 103–106.

Из всего комплекса параметров молнии важнейшее значение имеют следующие параметры видимого канала молнии: значение максимального тока, длительность фронта и волны молнии, изменение тока во времени и т.п. Эта статья будет полезна для решения проблем, возникающих при проектировании и устроистве молниезащиты в Литве. Ил. 2, библ. 4 (на английском языке; рефераты на английском, русском и литовском яз.).

N. Bagdanavičius, A. Drabatiukas, Š. Kilius. Žaibo išlydžio parametrai pastatų žaibosaugos skaičiavimuose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 3(91). – P. 103–106.

Iš viso komplekso žaibo elektrinių parametrų didžiausią reikšmę turi jo matomo kanalo srovės parametrai – maksimali srovės vertė, srovės bangos fronto trukmė, impulso trukmė, srovės kitimo laikui bėgant ypatumai ir kt. Šis straipsnis padės spręsti praktines problemas, kylančias projektuojant ir įrengiant Lietuvoje objektų žaibosaugos priemones. Il. 2, bibl. 4 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).