Nature of Atmospheric Discharges

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This article presents simplified description of the phenomenon of lightning, with special regard to the cloud-to-ground discharges, and parameters of standardized lightning electromagnetic pulses. Measures of protection against lightning are pointed out. These parameters and measures are important for proper lightning protection of telecommunication facilities.

Lightning Electromagnetic Pulse (LEMP), lightning phenomenon, protection against lightning

Introduction

The natural phenomenon of lightning has previously been treated mainly as a fire hazard or a threat for living beings. In parallel with technological progress, lightning has become a significant threat for electronic devices, especially for telecommunication sites.

Lightning protection is one of important engineering challenges. The protection measures may be chosen properly if the design process is based on knowledge about the nature and parameters of the atmospheric discharges. There are many publications concerning these topics, i.e. [1]-[11]. However, many engineers do not read them for different reasons. Understanding the lightning protection rules is not very common. It is often seen that opportunistic marketing leads to unnecessary or sometimes even hazardous selections. Hence, there is a need of publishing of considerably short papers in engineering journals and magazines, concerning basics of lightning protection and describing this in a simplified but nontrivial manner. The present paper belongs to that group of publications.

The electrostatic phenomena accompany different processes occurring in the atmosphere. The electric field of about 130 V/m exists close to the ground even during a sunny day in the mid-latitudes. The typical potential difference between the Earth's surface and the lower part of the ionosphere is from 200 to 500 kV. Due to this, a so-called fair-weather current of density of several pA/m^2 flows in the air.

The electric nature of lightning is known from about 260 years. It was proved by Benjamin Franklin during his famous kite experiment in year 1752. This experiment gave the basis for invention of a lightning rod. In Poland, Józef Osiński was the pioneer of lightning protection. He was the priest and lecturer in physics and chemistry in the Piarists Collegium Nobilium in Warsaw. Under his influence the first lightning rod was installed on the clock tower of the Royal Castle in Warsaw in year 1784.

The foundations of modern knowledge about the distribution of electrical charges in the storm clouds were developed at the beginning of the twentieth century. A special role was played by two British scientists G. C. Simpson and C. T. R. Wilson.

Simpson measured the loads carried by raindrops directly beneath the clouds. Later, he developed a tool to measure the vertical component of the electric field from the balloon deep into the clouds. Wilson studied the changes in the electric field accompanying lightning bolts at a distance from clouds, and on this basis, he determined the value and polarity of discharge in the clouds, and between clouds and the ground. Wilson was awarded the Nobel Prize in year 1927 (together with A. H. Compton) for his research on the electric charges in so-called storm cell. Three regions with dissimilar electrostatic polarization are present in a thundercloud: the highest is a large area of positively charged ice crystals, the lower part is dominated by the negative charge, and at the cloud base there is a small zone of positive polarity.

Atmospheric discharges are classified as:

- cloud-to-ground (CG),
- intracloud (IC), occurring wholly within the cloud - well over 50% of all flashes,
- cloud-to-cloud,
- cloud-to-air (including ionosphere).

Cloud-to-cloud and cloud-to-air discharges occur less frequently than either IC or CG lightning. About 2000 thunderstorms take place on the Earth at any moment. Within every second about 100 lightning strikes of any type, not only CG, are recorded on average all around the globe. This gives an average density of discharges of about 6 per km^2 per year. The average year density of discharges in the lands ranges from 2 to 5 per km^2, and in areas with the highest storm activity – up to 50 per km^2. In Poland, the average number of stormy days per year vary from less than 16 (north) to 36 (south) [12]. Temperature of plasma in the lightning channel reaches 30000ºC, exceeding five times the surface temperature of the Sun.

Information on lightning is provided by experimental studies. Research centers are located in areas of high storm activity, where discharges are provoked by rockets fired toward the clouds. Such centers are located, for example, in the United States – in Florida and New Mexico, in Australia – on Melville Island. Studies using rockets were also performed in France and Japan. There are many publications of natural discharge measurements carried out on high building objects, such as the Canadian National (CN) Tower in Toronto, broadcasting towers of Ostankino in Moscow and Peissenberg in Germany. Electronic systems for lightning detection are developed around the world.

Classification of cloud-to-ground discharges

There are much more experimental data concerning the cloud-to-ground (CG) discharges than other forms of lightning. This is because the consequences of the CG lightning are very important in practice, i.e. the ignition of fires, the cause of injuries and death, disturbances in power and communication systems. Moreover, the studies of lightning below the cloud base are less difficult.

The charge neutralization with an average value of about 20-30 coulombs takes place during a CG flash. The typical length of the discharge channel is a few kilometers.

The initial stages of the four main types of CG discharges, according to the classification given by Uman [10], [11], are presented in Fig. 1. The placed further description of atmospheric discharges comprises their most important characteristic electrical parameters. Detailed analysis of the phenomenon of lightning lies outside the scope of this work. Comprehensive descriptions can be found for example in [3], [4], [8], [11].

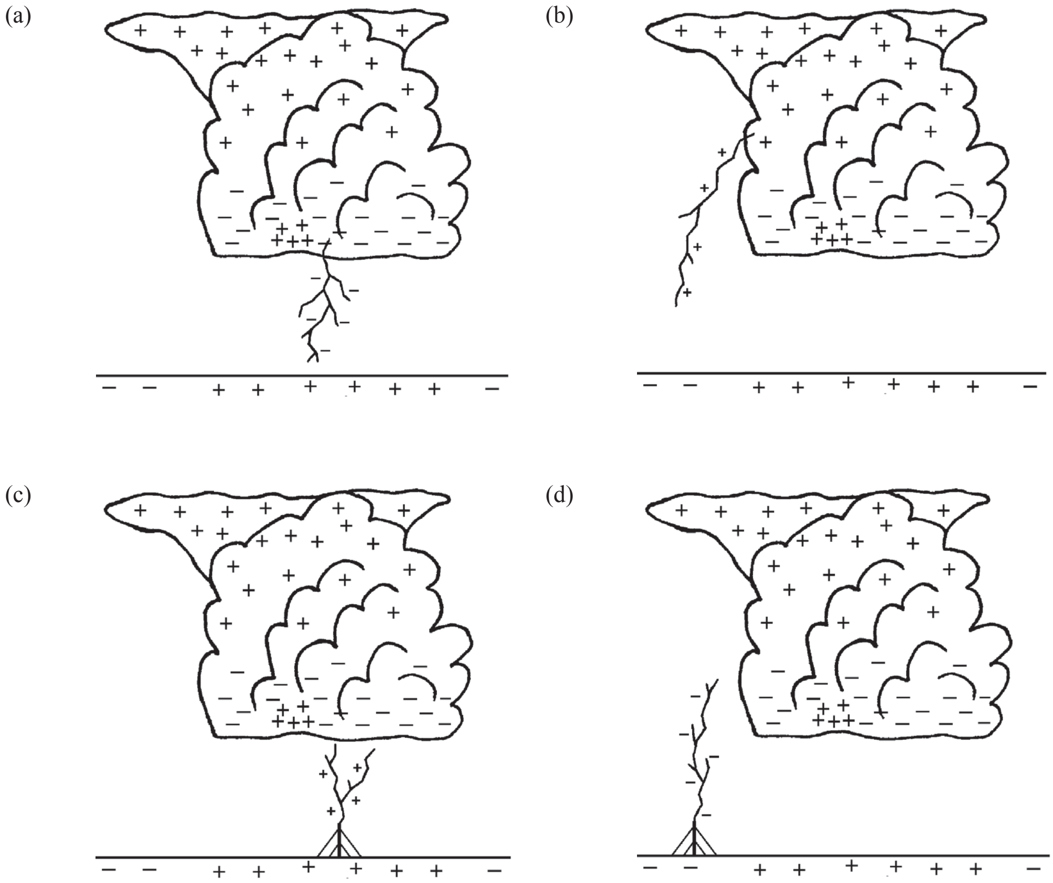

Fig. 1. *Four types of development of CG flashes according to Uman: a) negative descending leader, b) positive descending leader, c) positive ascending leader, d) negative ascending leader*

Simplified description of most frequent cloud-to-ground discharge

A negatively charged descending leader, as shown in Fig. 1a and Fig. 2a, is the first phase of about 90% of CG flashes. From the place of discharge initiation inside the cloud, the leader moves towards the ground with steps of tens of meters in length, and an average speed of about 200 km/s. These steps might be branched and pass in different directions. The duration of a typical step is about 1 µs, and the intervals between successive jumps last from 20 to 50 µs. The average leader current is of 100 to 1000 A.

As the lowering of the leader, the electric field near the ground increases from the initial value of several kV/m to over 150 kV/m. Such large gradient of potential results in the development of partial discharges and sending upward streams of positive ions (St. Elmo's fires) from sharp ends of various objects, where the local field strength is the greatest (Fig. 2b). Several tens of meters above the ground one of these so-called streamers meets with descending leader, closing the discharge channel.

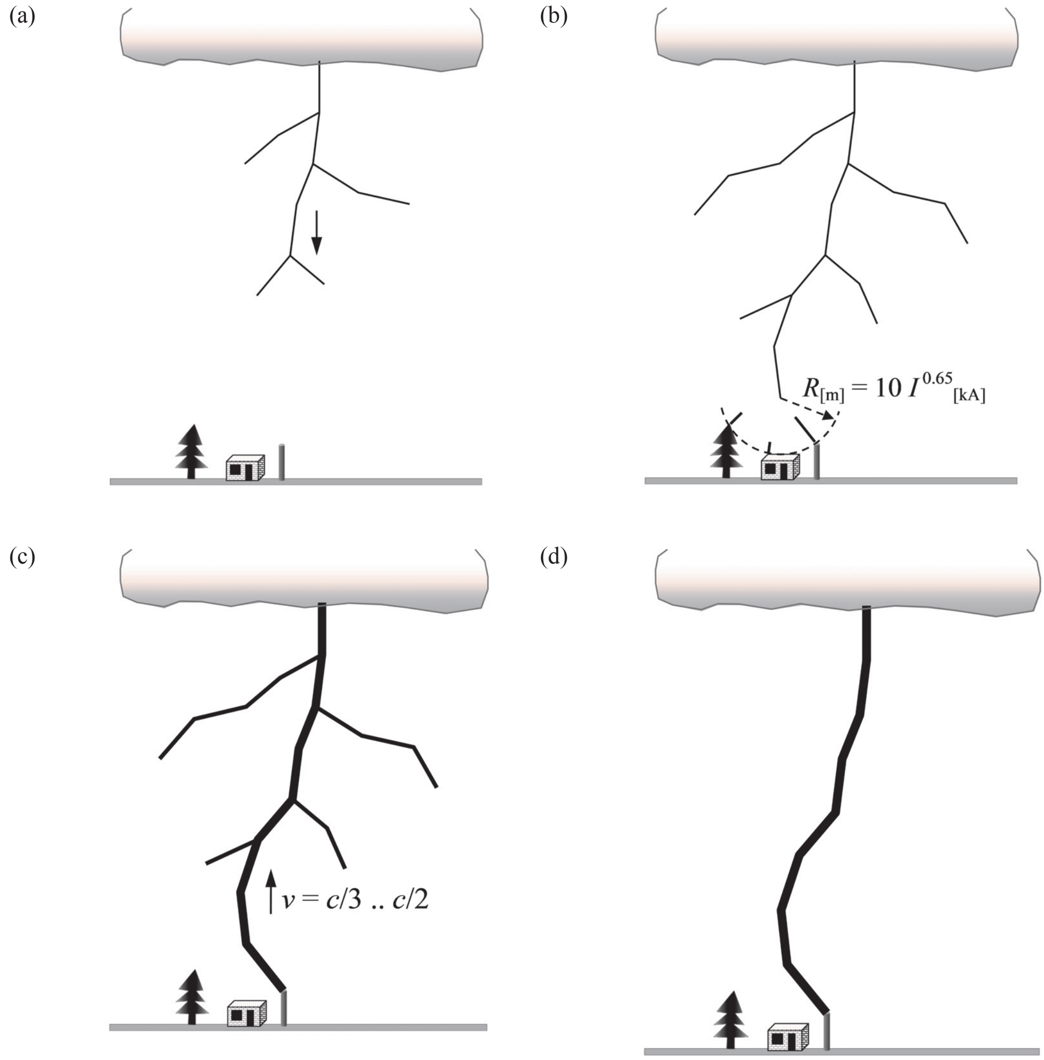

Fig. 2. *Main phases of negative CG flash: a) negative stepped leader developing downwards, b) streamers developing upwards, c) return stroke developing upwards, d) subsequent stroke*

The next phase is the return stroke (Fig. 2c). The electric charge accumulated in the channel and its branches is violently brought to the ground. The process of charge neutralization in the lightning channel develops in the direction from ground to the cloud at a speed of about 1/3 to 1/2 of that of light. A typical maximum value of the lightning current close to the ground is about 30 kA (the maximum current of 200 kA is predicted in the IEC/EN standard [6]). A high-temperature high-pressure discharge channel expands and creates the shock wave becoming thunder.

The rise of the return current pulse takes single microseconds. Fading of the discharge current is described by the time of decreasing to the half of peak value, which is on average of about 50 µs. The waveform of the lightning current pulse is standardized [6]. Three parameters are used to describe the current: I_{max} – maximum value, T_1 – front time, and T_2 – time to half-value (Fig. 3), in the form of I_{max}, T_1/T_2, i.e. 20 kA, 2/50 µs.

At the end of the main surge, the long stroke component of several hundred amperes can occur, which can last for several hundred milliseconds. After the first return stroke, different charge motion processes occur in the cloud. They are described in detail in [8], [11]. If additional cloud charge is available, a so-called dart leader can propagate down the residual channel of plasma, and initiate a subsequent return stroke (Fig. 2d). Several subsequent return strokes can occur in one channel. Dart leaders and subsequent return strokes are usually not branched. A long stroke current component can follow the subsequent return stroke. The time between successive strokes is usually several tens of milliseconds. This can be noticed with the naked eye as a flickering of lightning. In comparison with the first return stroke, the subsequent discharges have usually smaller maximum current, a much shorter front time (a fraction of a microsecond) and a shorter time to half value.

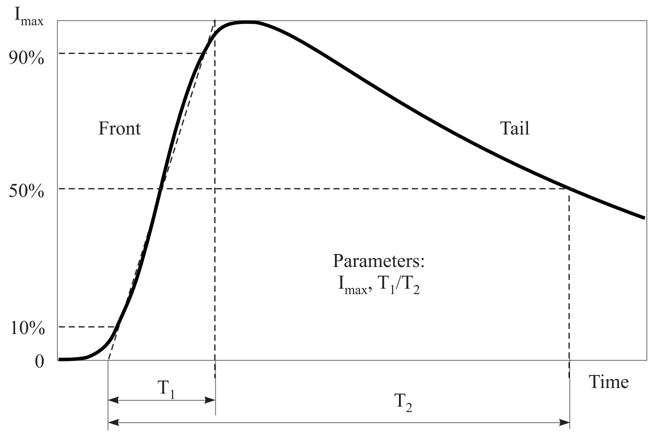

Fig. 3. *Standardized waveform of lightning current*

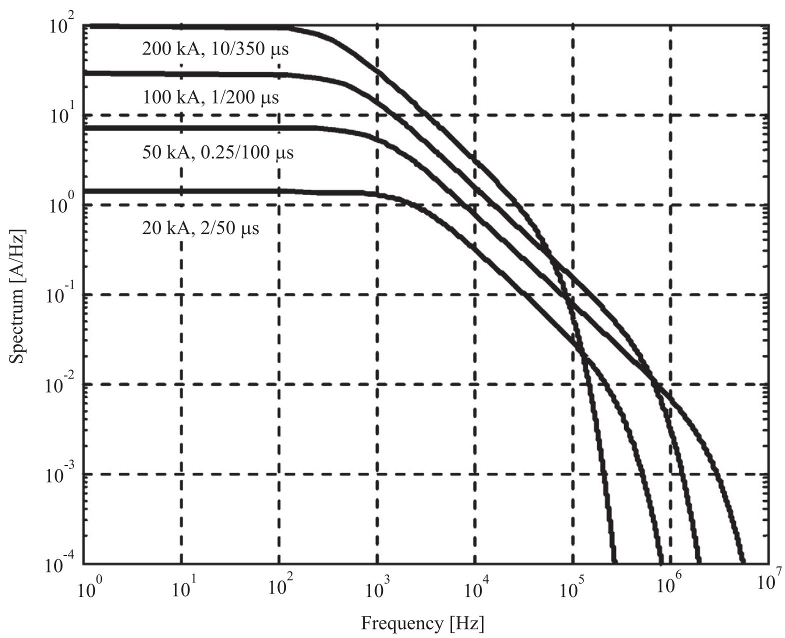

Fig. 4. *Amplitude spectra of standard pulses*

Other atmospheric discharges

Positive cloud-to-ground discharges, developing as shown in Fig. 1b are observed much less frequently than the phenomenon described above. Positive leaders from upper parts of clouds do not have as distinct steps as the negative ones. Usually there is only one positive stroke, transferring much greater charge than the negative one. Positive strokes are the majority of strokes to ground during winter storms. They are relatively rare in summer thunderstorms; only few percent of all the summer CG flashes are positive, often appearing at the beginning or at the end of the storm.

Cloud-to-ground discharges developing from the ground towards the cloud are relatively rare. They most frequently initiate from tops of tall objects such as towers, antennas, trees on hills, or rockets fired towards clouds in order to provoke lightning.

Other types of discharges, i.e. intracloud (IC), cloud-to-cloud and cloud-to-air, are not well studied. Typical IC discharges carry charges of tens of coulombs at a distance 5-10 km. Discharges between clouds can reach length exceeding 150 km. Measurements of accompanying electromagnetic fields exhibit significant similarities between IC and cloud-to-cloud discharges.

There are reports describing blue sky overhead and a thunderstorm more than 10 km away, beyond the horizon, from where the lightning can originate. Such phenomenon is called “bolt from the blue” [10].

Flights above clouds and flights of space shuttles enable observations of upper-atmospheric discharges called TLEs – Transient Luminous Events (elves, blue jets, red sprites). They extend up to 100 km above the ground.

Electrical parameters of lightning

The lightning protection can be effective if the parameters of lightning stroke are determined. The greatest threat is caused by a return stroke. Hence, according to the first (the highest) protection level introduced in IEC/EN 62305-1 [6], maximum values for return stroke currents are specified as follows:

- first positive return stroke – pulse of 200 kA, 10/350 μs,
- first negative return stroke – pulse of 100 kA, 1/200 μs,
- subsequent negative return stroke – pulse of 50 kA, 0.25/100 μs,
- long stroke component – 400 A, duration 0.5 s.

The analysis of lightning current spectrum is important, especially for telecommunication facilities. Plots of amplitude spectra of standard pulses mentioned above, and of waveform 20 kA, 2/50 μs, used in former Russian standards, are presented in Fig. 4. It is seen that the frequency band, which contains a majority of the pulse energy, reaches approximately 100 kHz. However, by the fact that it is a large amount of energy, the frequency band up to 10 MHz should be taken into account. More details can be found in [6].

The threat posed by lightning electromagnetic pulse (LEMP) is described not only by the current parameters, but also by associated electric and magnetic fields. Induced overvoltage surges can cause damages of electronic devices at a distance exceeding 1.5 km from the lightning channel. At a distance of several meters from the lightning channel, the electric field strength has a value of several hundred kV/m, at a distance of several tens of meters – tens of kV/m, at few hundred meters – few kV/m. Over 100 V/m is reached even at a distance of tens kilometers away from the discharge.

The magnetic field strength has a value of several kA/m at a distance of meters from the lightning channel, and it reaches hundreds of A/m within hundreds of meters.

The analysis of spectrum of the electromagnetic field associated with the whole phenomena of lightning, not only with the return stroke, is important also for remote lightning location systems, to distinguish between cloud discharges and discharges to ground [8].

Standard and non-standard lightning protection

Modern lightning protection applies not only to buildings, but also to internal installations and devices. The lightning and overvoltage protection comprises the following measures [6]:

- an outer mesh of air terminals and down conductors,
- an earth electrode system,
- direct bonding (equipotentialization),
- surge protective devices (SPDs) in the power supply network,
- SPDs in signal lines (telephones, computer network, antennas),
- appropriate cable routing,
- safe isolation distances,
- interference suppression filters,
- shielding,
- physical restrictions and warning messages.

The outer wire mesh together with the earth electrode system is called the lightning protection system (LPS). The LPS mesh dimensions are standardized, and the density of this wire mesh varies depending on the assumed level of protection (and the protection effectiveness).

There are many devices present at the market that are inconsistent with the IEC/EN standards. There are two main groups of them, called early streamer emitters (ESE, or "active" lightning rods) and "lightning preventers" [13]-[14]. The ESE devices are claimed to be able to capture the lightning to them, having extremely large protected zone in comparison to the standard air terminals. The lightning prevention air terminals (charge dissipaters) are claimed to be able to prevent lightning from occurring.

Neither data nor theory supports claims that "lightning elimination" and "early streamer emission" techniques are superior to standard lightning protection systems [14]. These devices are expensive, and methods of installation proposed by vendors may sometimes result in additional electromagnetic threats, including danger to life [15].

Essential principle of protection

The essential principle of protection against any type of electromagnetic disturbances, not only lightning, is that a design engineer should determine a boundary, on which the unwanted signals (voltages, currents, and electromagnetic fields) are limited to the desired level. As a rule, this boundary is formed by natural barriers - walls of a building, a room, or an equipment box. This principle forms a basis for the concept of lightning protection zones (LPZ) [6].

Every protective device should be installed on the determined boundary, so as not to let the unwanted signals to penetrate the protected volume. The commonly met error is that protective devices (mainly SPDs) are mounted far from the boundary, inside or outside the protected volume.

First aid

According to IEC/TR 60479-4:2004 [7] it is accepted that 70% or more lightning accidents involving humans are not fatal. Corresponding reliable data for livestock (animals) are not known. The chance of survival strongly depends on first aid, which is similar to the first aid after electric shock - to restore the respiration and the heart action.

Conclusion

Basic information concerning the lightning phenomenon and the parameters of lightning electromagnetic pulse and understanding of these facts is essential for the proper design of lightning protection of telecommunication facilities.

The most important topics of lightning protection are design and realization of lightning protection systems, grounding, bonding (equipotentialization) techniques, cable routing, location of surge arresters. Most lightning damages met in building objects could be avoided if all the electric and electronic installations were made according to appropriate IEC/EN standards.

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