CIGRE Technical Brochure on Lightning Parameters for Engineering Applications

RAKOV V.A. *Professor of the Department «Electrical and Computer Engineering» of the Florida University*

In April 2008, CIGRE (International Council on Large Electric Systems) formed a new Working Group C4.407, named "Lightning Parameters for Engineering Applications". That was an initiative of Prof. C.A. Nucci (then Convener of the CIGRE Study Committee C4) and Prof. M. Ishii (Convener of the Advisory Group C4.4). The WG C4.407 was composed of 21 members from North and South America, Europe, and Asia. It was tasked to prepare a CIGRE Reference Document (Technical Brochure) on lightning parameters needed for engineering applications. CIGRE WG C4.407 has completed its work on the Technical Brochure in May 2013. This Brochure (CIGRE TB 549, 2013) can be viewed as an update on previous CIGRE documents on the subject published in Electra more than three decades ago: Berger et al. (1975) and Anderson and Eriksson (1980). This review paper is largely a presentation of the Executive Summary of CIGRE TB 549 (2013), expanded to include some illustrations.

General Characterization of Lightning. About 80% or more of negative cloud-to-ground lightning flashes are composed of two or more strokes. This percentage is appreciably higher than 55% previously estimated by Anderson and Eriksson (1980), based on a variety of less accurate records. The average number of strokes per flash is typically 3 to 5, with the geometric mean interstroke interval being about 60 ms. Roughly one-third to one-half of lightning flashes create two or more terminations on ground separated by up to several kilometers (see Fig. 1). When only one location per flash is recorded, the correction factor for measured values of ground flash density to account for multiple channel terminations on ground is about 1.5–1.7, which is considerably larger than 1.1 previously estimated by Anderson and Eriksson (1980). Bouquegneau et al. (2012) suggested a conservative value of 2 for lightning risk calculations recommended by the IEC Standard. First-stroke current peaks are typically a factor of 2 to 3 larger than subsequent-stroke current peaks. However, about one third of cloud-to-ground flashes contain at least one subsequent stroke with electric field peak, and, by theory, current peak, greater than the first-stroke peak.

Return-Stroke Parameters Derived from Current Measurements. From direct current measurements, the median return-stroke peak current is about 30 kA for negative first strokes in Switzerland, Italy, South Africa, and Japan, and typically 10–15 kA for subsequent strokes in Switzerland and for triggered and upward (object-initiated) lightning. Corresponding values from measurements in Brazil are 45 kA and 18 kA. Additional measurements are needed. The "global" distributions of lightning peak currents for negative first strokes currently recommended by CIGRE and IEEE are each based on a mix of direct current measurements and less accurate indirect measurements, some of which are of questionable quality. However, since the "global" distributions have been widely used in lightning protection studies and are not much different from that based on direct measurements only (median = 30 kA, $s_{1g} I = 0.265$ for Berger et al.'s distribution), continued use of these "global" distributions for representing negative first strokes is recommended. For negative subsequent strokes, a log-normal distribution with median = 12 kA and $s_{1g} I = 0.265$, where ylg is the standard deviation of base-10 logarithm, should be used. For positive lightning strokes, a log-normal distribution with median = 35 kA and $s_{1g} I = 0.544$ is recommended, although the data are very limited and may be influenced by the presence of strike object located on the mountain top (see Fig. 2). Direct lightning current measurements on instrumented towers should be continued. Currently, direct current measurements are performed on instrumented towers in Austria, Brazil, Canada, Germany, Japan, and Switzerland, although the overwhelmimg majority of observed flashes (except for Brazil and possibly Japan) are of upward type.

Recommended lightning current waveshape parameters are still based on Berger et al.'s (1975) data, although the current rate-of-rise parameters estimated by Anderson and Eriksson (1980) from Berger et al.'s oscillograms are likely to be significantly underestimated, due to limitations of the instrumentation used by Berger et al. Triggered-lightning data for current rates of rise can be applied to subsequent strokes in natural lightning. Relatively strong correlation is observed between the lightning peak current and charge transfer and between the current rate-of-rise characteristics and current peak, and relatively weak or no correlation between the peak and risetime.

Peak Current Inferred from Measured Electromagnetic Field. The field-to-current conversion procedure employed by the U.S. National Lightning Detection Network (NLDN) and other similar lightning locating systems has been calibrated only for negative subsequent strokes, with the median absolute error being 10 to 20%. Peak current estimation errors for negative first strokes and for positive lightning are presently unknown. Besides systems of NLDN type (such as the European systems participating in

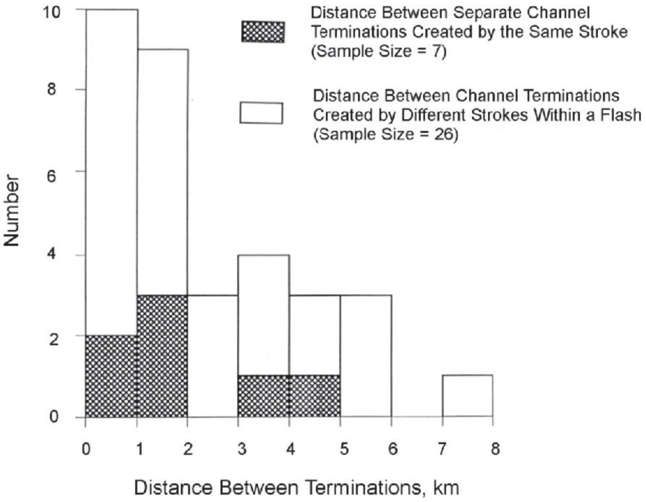

Fig. 1. Histogram of the distance between the multiple terminations of 22 individual ground flashes in Florida. Adapted from Thottappillil et al. (1992)

EUCLID or nationwide and regional systems in Japan), there are other lightning locating systems that are also reporting lightning peak currents inferred from measured fields, including LINET (mostly in Europe), USPLN (in the U.S., but similar systems operate in other countries), WTLN (in the U.S. and other countries), WWLLN (global), and GLD360 (global). Peak current estimation errors for the latter three systems are presently being examined using triggered-lightning data.

Continuing Currents. The percentage of positive flashes or strokes containing continuing currents (CC) is much higher than those of negative flashes or strokes. Positive strokes tend to be followed by longer and more intense CC than negative strokes. In contrast with negative strokes, positive strokes can produce both a high peak current and a long CC. Waveshapes of CC in natural cloud-to-ground flashes may be grouped into six categories. The average number of M components (surges superimposed on continuing currents) per CC appears to depend on polarity: while an average of 5.5 M components per CC were observed for negative flashes, an average of 9.0 M components per CC were observed for positive flashes. It has been inferred that strokes initiating long CC in negative flashes tend to have a lower peak current and are preceded by higher-peak-current strokes and by relatively short interstroke intervals.

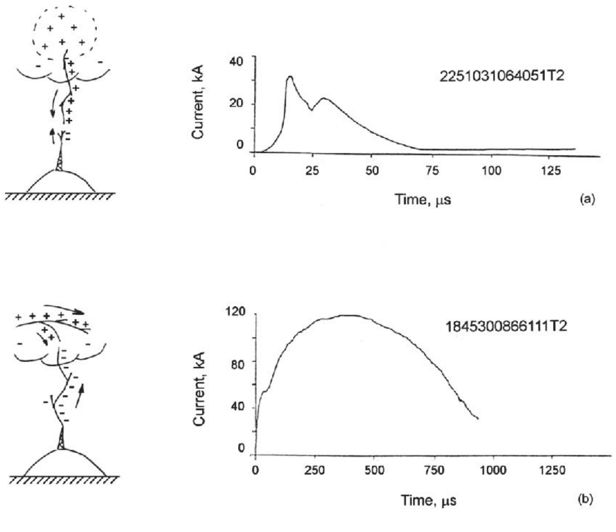

Fig. 2. Examples of two types of positive lightning current vs. time waveforms observed by K. Berger: (a) microsecond-scale waveform, similar to those produced by downward negative return strokes, and a sketch illustrating the lightning processes that might have led to the production of this waveform; (b) millisecond-scale waveform and a sketch illustrating the lightning processes that might have led to the production of this current waveform. Arrows indicate directions of the extension of lightning channels. Adapted from Rakov (2003)

Lightning Return Stroke Propagation Speed. The lightning return-stroke speed is needed in computing lightning electromagnetic fields that cause induced overvoltages in power distribution lines. It is also explicitly or implicitly assumed in procedures to infer lightning currents from measured fields. The average propagation speed of a negative return stroke (first or subsequent) below the lower cloud boundary is typically between one-third and one-half of the speed of light. It appears that the return-stroke speed for first strokes is lower than that for subsequent strokes, although the difference is not very large (9.6´ 107 vs. 1.2 x 108 m/s). For positive return strokes, the speed is of the order of 108 m/s, although data are very limited. The negative return-stroke speed within the bottom 100 m or so (corresponding to current and field peaks) is expected to be between one-third and two-thirds of the speed of light. The negative return stroke speed usually decreases with height for both first and subsequent strokes. There exists some experimental evidence that the negative return stroke speed may vary non-monotonically along the lightning channel, initially increasing and then decreasing with increasing height. There are contradicting data regarding the variation of positive return stroke speed with height. The often assumed relationship between the return-stroke speed and peak current is generally not supported by experimental data.

Equivalent Impedance of the Lightning Channel. The equivalent impedance of the lightning channel is needed for specifying the source in studies of either direct-strike or induced lightning effects. The estimates of this impedance from limited experimental data suggest values ranging from several hundred ohm to a few kiloohm. In many practical situations the impedance “seen” by lightning at the strike point is some tens of ohm or less, which allows one to assume infinitely large equivalent impedance of the lightning channel. In other words, lightning in these situations can be viewed as an ideal current source. In case of direct lightning strike to an overhead conductor of a power line with 400 ohm surge impedance (effective resistance 200 ohm, since 400 ohm is “seen” in either direction), the ideal current source approximation may still be suitable. Representation of lightning by a current source with internal impedance of 400 ohm, similar to that of an overhead wire, is probably not justified.

Positive and Bipolar Lightning Discharges. Although positive lightning discharges account for 10% or less of global cloud-to-ground lightning activity, there are several situations, including, for example, winter storms, that appear to be conducive to the more frequent occurrence of positive lightning. The highest directly measured lightning currents (near 300 kA vs. a maximum of about 200 kA or less for negative lightning) and the largest charge transfers (hundreds of coulombs or more) are associated with positive lightning. Positive flashes are usually composed of a single stroke, although up to four strokes per flash have been observed. Subsequent strokes in positive flashes can occur either in a new (a more common situation) or in the previously-formed channel. In spite of recent progress, our knowledge of the physics of positive lightning remains considerably poorer than that of negative lightning. Because of the absence of other direct current measurements for positive lightning return strokes, it is still recommended to use the peak current distribution based on the 26 events recorded by K. Berger, even though some of those 26 events are likely to be not of return-stroke type (see Fig. 2). However, caution is to be excersized, particularly for the waveshape parameters, for which sample sizes are smaller than for peak currents. Clearly, additional measurements for positive lightning return strokes are needed to establish reliable distributions of peak current and other parameters for this type of lightning. Bipolar lightning discharges are usually initiated by upward leaders from tall objects. However, natural downward flashes also can be bipolar.

Upward Lightning Discharges. Tall objects (higher than 100 m or so) located on flat terrain and objects of moderate height (some tens of meters) located on mountain tops experience primarily upward lightning discharges that are initiated by upward-propagating leaders. The percentage of upward flashes increases with increasing object height. Upward (object-initiated) lightning discharges always involve an initial stage that may or may not be followed by downward-leader/upward-return-stroke sequences. The percentage of upward flashes with return strokes varies from 20 to 50%. The initial-stage steady current typically has a magnitude of some hundreds of amperes and often exhibits superimposed pulses whose peaks range from tens of amperes to several kiloamperes (occasionally a few tens of kiloamperes). Object-initiated lightning events may occur relatively independently from downward lightning during the non-convective season, and it has been observed that in many cases several flashes were initiated from a tall object within a period of some hours. At tall objects, the probability of occurrence of bipolar lightning is about the same as for positive lightning. Possible reasons for the observed differences between the downward lightning and the high-complexity upward lightning are the multiple upward branches of the leader initiated from the tower and the relative proximity of the cloud charge regions to the object tip.

Geographical and Seasonal Variations in Lightning Parameters. From the information available in the literature at the present time, there is no evidence of a dependence of negative cloud-to-ground lightning parameters on geographical location, except maybe for first and subsequent return-stroke peak currents, for which relatively insignificant (less than 50%), from the engineering point of view, variations may exist. It is important to note, however, that it cannot be ruled out that the observed differences in current measurements are due to reasons other than «geographical location», with the limited sample size for some observations being of particular concern. Similarly, no reliable information on seasonal dependence is available. In summary, at the present time, the available information is not sufficient to confirm or refute a hypothesis on dependence of negative CG lightning parameters on geographical location or season. On the other hand, some local conditions may exist (for example, winter storms in Japan) that give rise to more frequent occurrence of unusual types of lightning, primarily of upward type, whose parameters may differ significantly from those of “ordinary” lightning. Further studies are necessary to clarify those conditions and their possible dependence on geographical location.

Lightning Parameters Needed for Different Engineering Applications. Lightning parameters needed for specific engineering applications are summarized. The emphasis is placed on the parameters that have an influence in the electric power engineering calculations, although lightning parameters needed for designing lightning protection of ordinary ground-based structures are also discussed.

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Техническая брошюра СИГРЭ «Параметры молнии для инженерных применений»

В.А. РАКОВ

В апреле 2008 г. СИГРЭ (Международный Совет по Большим Электрическим Системам) сформировал Рабочую группу С4.407 (WG C4.407) «Параметры молнии для инженерных применений». В состав WG C4.407 входил 21 член из Северной и Южной Америки, Европы и Азии. Задачей этой Рабочей группы была подготовка Технической Брошюры «Параметры молнии для инженерных применений». Работа была завершена в мае 2013 г. Техническая брошюра (CIGRE TB 549, 2013) может рассматриваться как обновленный с учетом современных данных вариант предыдущих документов СИГРЭ на эту тему, опубликованных более трех десятилетий назад (REFERENCES: No. 1 и 2). Данная обзорная статья представляет собой расширенное резюме Технической брошюры CIGRE TB 549 (2013) с соответствующими иллюстрациями и включает следующие разделы:

Общие характеристики молнии
Параметры главной стадии (возвратного удара), полученные по измерениям тока
Пиковые токи, полученные по измерениям электромагнитных полей
Затяжные токи
Скорость распространения возвратного удара
Эквивалентное сопротивление канала молнии
Положительные и биполярные разряды
Восходящие разряды
Географические и сезонные вариации параметров молнии
Параметры молнии, требующиеся для различных инжен6ерных применений

*Автор: **Раков Владимир** – профессор Университета Флориды (США).*