Lightning Parameters for Engineering Applications

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To the electric utility engineer, the parameters of the flash that are of primary interest are the crest current for the first and subsequent strokes, the waveshape of these currents, correlation between the parameters, the number of strokes per flash and flash incidence rates where the ground flash density, denoted as flashes per square km-year and symbolised by N_g.

The charge lowered by the flash and perhaps the integral of the current squared, frequently called the 'action integral, may also be of some interest. The first three parameters, as we know them today, are to a very large extent based on the measurements of Berger. Berger's masts, 70-80 metres high, were mounted on the top of Mt. San Salvatore (Switzerland), which is 650 metres above Lake Lugano.

Although 75% of the 1,196 flashes measured were negative upward, about 11% or 125 flashes were negative downward. When it was realised that Berger made oscillographic recordings of the currents in both the first and the subsequent strokes of the flash, making all waveshape parameters and their correlation available, it was readily noted that these 125 records represented one of the best and most extensive sets of data available to the industry to date. Several studies were done to take photos of the lightning, where the natural lightning channel usually has a 'zigzag' shape with some branches. In addition, the triggered lightning channel usually has a straight shape (or at least at some hundred metres to the ground surface) without any branches. While the triggered lightning remains an important method for the validation of the calculated electric and magnetic fields, this issue of vertical and inclined channel, for instance, remains as one of the parameters that need to be considered which can result in inaccuracy of the calculation.

INTRODUCTION

Lightning is one of the most fantastic natural phenomena in the world. It can result in severe damage to property. Lightning happens when a region of atmosphere acquires a sufficiently huge electric charge that is capable of causing an electrical breakdown. It has been reported that there are 2,000 thunderstorms in progress at any time, resulting in 100 lightning flashes to ground per second; this is 8 million per day. Lightning is the cause of around 100 deaths and 250 injuries in the United States each year, more than from any other weather-related phenomenon.

Even though there is no database available with regards to the victims or survivors due to the lightning, there are some well documented cases, especially related to injuries and deaths caused by the lightning. It has become a significant threat in many countries where the natural phenomenon has previously, been thought of as affecting only those who are careless. Most tropical countries, several southern states of the USA, Japan and several parts of Australia, experience heavy annual lightning occurence density (1)-(12).

Malaysia encounters more than 70% of power outages due to lightning and we are known as the Crown Of Lightning in the world. The effects of lightning on electrical and communication networks and structures account for equipment damage, downtime/data losses and malfunction of control and automated systems. All these cost the nation over RM250 million annually, not to mention thousands of cases of human injuries and deaths. Both lightning and intentionally generated lightning-like microwave pulses may also disrupt civil and defence systems, giving rise to serious threats to national security.

Malaysia is ranked among the top three countries in the world in terms of lightning density, more than any other country in Asia. Human lives can be saved if people are given proper education in lightning protection. Apart from human injuries and deaths, another matter of concern is the deaths of many animals caused by lightning every year. At present, available protection technologies in Malaysia are more suited to non-tropical environments; the market is also controlled and dominated by developed nations which make over RM50 million in profit from such protection.

This paper highlights some of the selected parameters of interests based on previous CIGRE documents on the subject, published in ELECTRA more than three decades ago by Berger *et al.*, (13), and Anderson and Eriksson (14).

SOME LIGHTNING PARAMETERS OF INTEREST

1. GROUND FLASH DENSITY

This is a fundamental parameter, providing the basis for any estimation of the frequency of lightning effects on electrical system. The ground flash density, N_g, is often viewed as the primary descriptor of lightning incidence, at least in lightning protection studies. Ground flash density has been estimated from records of (1) lightning flash counters or LFCs and (2) lightning locating systems or LLSs. This can potentially be estimated from records of satellite-based optical or radio-frequency radiation detectors. It is worth noting that satellite detectors cannot distinguish between cloud and ground discharges, so in order to obtain N_g maps from satellite observations, a spatial distribution of the fraction of discharges to ground relative to the total number of lightning discharges, is needed. In the absence of ground-based measurements of N_g, IEEE Std 1410-2010 (15) recommends to assume that N_g is equal to one-third of the total flash density (including both cloud and ground discharges) based on satellite observations.

The ground flash density N_g for temperate areas may be estimated from T_d, the keraunic level, using Equation (1) from Anderson *et al.*, (B6):

$$N = 0.04T_d^{1.25} \qquad (1)$$

where

N_g is the ground flash density in flashes per sqkmper year
T_d is the number of days with thunder per year.

Torres *et al.*, (16) noted that this expression has unacceptably large errors in tropical areas, recommending the alternative expressions for Equation (1), as tabulated in Table 1:

Table 1: Alternative expressions for Equation 1 for tropical areas.

Country	Alternative expression for Equation (1)
Mexico	$N = 0.024T_d^{1.12}$
Brazil	$N = 0.030T_d^{1.12}$
Columbia	$N = 0.0017\ T_d^{1.56}$

2. PEAK CURRENT – "CLASSICAL" DISTRIBUTION

Basically, all national and international lightning protection standards (e.g., IEEE Std 1410-2010 (15); IEEE Std 1243- 1997 (17); IEC 62305 series (18-21)) include a statistical distribution of peak currents for first strokes in negative lightning flashes (including single-stroke flashes). This distribution, which is one of the foundations of most lightning protection studies, is largely based on direct lightning current measurements conducted in Switzerland from 1963 to 1971.

It is worth noting that directly measured current wave forms of either polarity found in the literature, do not exhibit peaks exceeding 300 kA or so, although inferences from remotely measured electric and magnetic fields suggest the existence of currents up to 500 kA and even higher.

For the CIGRE distribution, 98% of peak currents exceed 4 kA, 80% exceed 20 kA, and 5% exceed 90 kA. For the IEEE distribution, the "probability to exceed" values are given by the following equation (2)

$$P(I) = \frac{1}{1 + (\frac{I}{31})^{2.6}} \qquad (2)$$

where P(I) is in per unit and I is the first return stroke peak current in kA. Note that this equation applies to values of I up to 200 kA.

According to Hileman (22), this equation, usually assumed to be applicable to negative first strokes, was based on data for 624 strokes analysed by Popolansky (23), whose sample included both positive and negative strokes, as well as strokes in upward lightning.

The distribution of subsequent-stroke peak current values was approximated in Equation (3) by (IEEE Std 1243-1997) (17):

$$P(I) = \frac{1}{1 + (\frac{I}{12})^{2.7}} \qquad (3)$$

Sample sizes for "global" peak current distributions for negative first strokes and the IEEE peak current distributions can be referred to CIGRE TB 549-2013 (18).

3. PEAK CURRENT: RECENT DIRECT MEASUREMENT

Recently, direct current measurements on instrumented towers were carried out in Russia, South Africa, Canada, Germany, Brazil, Japan, Austria and again in Switzerland (on a different tower). Important results from the Brazilian, Japanese, and Austrian studies were reviewed and compared with Berger's data. In addition, recent direct current measurements for rocket-triggered lightning were also considered.

Tables 2 and 3 summarised the distributions of lightning peak currents from individual studies (obtained from direct measurements only) and those synthesized by combining different measurements for first and subsequent stroke (18).

Table 2: Comparison of return-stroke peak currents (the largest peak, in kA) for first strokes in negative downward lightning

References	Location	Sample size	Percent exceeding tabulated value			$\sigma_{lg}I$	Remarks
			95%	50%	5%		
Berger et al. (1975)	Switzerland	101	14	30 (~30)	80	0.265	Direct measurements on 70-m towers
Anderson and Eriksson (1980)	Switzerland	80	14	31	69	0.21	Direct measurements on 70-m towers
Dellera et al. (1985)	Italy	42	-	33	-	0.25	Direct measurements on 40-m towers
Geldenhuys et al. (1989)	South Africa	29	7*	33 (43)	162*	0.42	Direct measurements on a 60-m mast
Takami and Okabe (2007)	Japan	120	10	29**	85	0.28**	Direct measurements on 40- to 140-m transmission-line towers
Visacro et al. (2012)	Brazil	38	21	45	94	0.20	Direct measurements on a 60-m mast
Anderson and Eriksson (1980)	Switzerland (N=125), Australia (N=18), Czechoslovakia (N=123), Poland (N=3), South Africa (N=11), Sweden (N=14), and USA (N=44)	338	9*	30 (34)	101*	0.32	Combined direct and indirect (magnetic link) measurements
CIGRE Report 63 (1991)	Switzerland (N=125), Australia (N=18), Czechoslovakia (N=123), Poland (N=3), South Africa (N=81), Sweden (N=14), and USA (N=44)	408	-	31 (33)	-	0.21	Same as Anderson and Eriksson's (1980) sample plus 70 additional measurements from South Africa

The 95%, 50%, and 5% values are determined using the lognormal approximation to the actual data, with 50% values in the parentheses being based on the actual data.

$\sigma_{lg}I$ is the standard deviation of the logarithm (base 10) of peak current in kA; $\beta = 2.3026\ \sigma_{lg}I$.

* As reported by Takami and Okabe (2007).

**26 kA and 0.32 after compensation for the 9-kA lower measurement limit.

Table 3: Comparison of return-stroke peak currents (in kA) for subsequent strokes in negative lightning

References	Location	Sample size	Percent exceeding tabulated value			$\sigma_{lg}I$	Remarks
			95%	50%	5%		
Berger et al. (1975)	Switzerland	135	4.6	12	30	0.265	Direct measurements on 70-m towers
Anderson and Eriksson (1980)	Switzerland	114	4.9	12	29	0.23	Direct measurements on 70-m towers
Dellera et al. (1985)	Italy	33	-	18	-	0.22	Direct measurements on 40-m towers
Geldenhuys et al. (1989)	South Africa	?	-	7- 8	-	-	Direct measurements on a 60-m mast
Visacro et al. (2012)	Brazil	71	7.5	18	41	0.23	Direct measurements on a 60-m mast
Diendorfer et al. (2009)	Austria	615	3.5	9.2	21	0.25	Direct measurements on a 100-m tower; upward lightning
Schoene et al. (2009)	Florida	165	5.2	12	29	0.22	Direct measurements; rocket-triggered lightning

The 95%, 50%, and 5% values are determined using the lognormal approximation to the actual data. $\sigma_{lg}I$ is the standard deviation of the logarithm (base 10) of peak current in kA; $\beta = 2.3026\ \sigma_{lg}I$. Data for strokes in upward and rocket-triggered flashes are included because those strokes are similar to subsequent strokes in natural downward flashes.

4. OTHER PARAMETERS

Apart from the basic parameter discussed earlier, there are several other lightning parameters needed in engineering applications include maximum current derivative, average current rate of rise, current rise time, current duration, charge transfer, and specific energy (action integral), which are all derivable from direct current measurements. Distributions of these parameters, presently adopted by CIGRE, are based on direct measurements by Berger and co-workers in Switzerland.

There are also more recent direct current measurements available which are obtained using instrumented towers in Austria, Brazil, Canada, Germany, Japan, Russia and Switzerland, as well as those obtained in several countries using rocket-triggered lightning. Furthermore, modern lightning locating systems report peak currents estimated from measured magnetic or electric field peaks. Additionally, lightning parameters such as the number of strokes per flash (multiplicity), interstroke interval, number of channels per flash, relative intensity of strokes within a flash, return-stroke speed, and equivalent impedance of the lightning channel, as well as characteristics of continuing currents and M-components are among other parameters to be considered. Table 4 shows lightning current parameters (based on Berger's data) recommended by CIGRETB 63 (24) and IEEE Std 1410-2010 (15).

SOME ENGINEERING APPLICATIONS

Lightning parameters are of interest in different fields of research and engineering applications, such as airborne vehicles, construction and oil industry engineering, power network components and wind turbines. The protection against lightning for each application follows specific standards.

Several aspects have been covered by previous CIGRETB 63 (19),TB 118 (1997), TB 172 (2000), TB 360 (2008), TB 287 (2006), TB 441 (2010) and by the ongoing activities of other working groups (e.g. WG C4.408 Lightning Protection of Low-Voltage Networks, WG C4.409 Lightning Protection of Wind Turbine Blades, WG C4.410 Lightning Striking Characteristics for Very High Structures, WG C4.23 Guide to Procedures for Estimating the Lightning Performance of Transmission Lines, WG C4.26 Evaluation of Lightning Shielding Analysis Methods for EHV and UHV DC and AC Transmission Lines).

Table 4: Lightning current parameters (based on Berger's data) recommended by CIGRETB 63 and IEEE Std 1410-2010

Parameters of log-normal distribution for negative downward flashes				
Parameter	First Stroke		Subsequent stroke	
	M, **Median**	**β, logarithmic (base e) standard deviation**	*M*, **Median**	**β, logarithmic base standard deviation**
FRONT TIME (µs)				
$t_{d10/90} = T_{10/90}/0.8$	5.63	0.576	0.75	0.921
$t_{d30/90} = t_{30/90}/0.6$	3.83	0.553	0.67	1.013
$t_m = I_F / S_m$	1.28	0.611	0.308	0.708
STEEPNESS (kA/µs)				
S_m, Maximum	24.3	0.599	39.9	0.852
S_{10}, at 10%	2.6	0.921	18.9	1.404
$S_{10/90}$, 10-90%	5.0	0.645	15.4	0.944
$S_{30/90}$, 30-90%	7.2	0.622	20.1	0.967
PEAK (CREST) CURRENT (kA)				
I_I, initial	27.7	0.461	11.8	0.530
I_F, final	31.1	0.484	12.3	0.530
Ratio, I_I/I_F	0.9	0.230	0.9	0.207
OTHER RELEVANT PARAMETERS				
Tail Time to Half Value t_h (µs)	77.5	0.577	30.2	0.933
Number of stokes per flash	1	0	2.4	0.96 based on median N_{total}=3.4
Stroke Charge, Q_I (Coulomb)	4.65	0.882	0.938	0.882
$\int I^2 dt$ ($(\mathrm{kA})^2 s$)	0.057	1.373	0.0055	1.366
Interstroke interval (ms)	-	-	35	1.066

In the case of transmission lines for instance, the protection is mainly based on the use of shield wires (or overhead ground wires) and selective use of surge arresters. Some special methods have also been successfully used for improving the lightning performance (17). Generally, the grounding system has a great influence on the effectiveness of the protection means. In the IEC 62305 series, those parameters are the basis of the developed standard for the protection of structures, living beings and electrical and electronic systems against lightning.

Effective shield wire protection is characterised by low probability of both shielding failures and back-flash-overs. Modelling and procedures for the estimation of these probabilities are addressed by both CIGRE document (24) and IEEE Standards (15, 17).

CONCLUSION

This paper has briefly discussed some of the basic lightning parameters that are needed in the power engineering calculations, along with relevant references to standards and the recent literature on the subject. Looking at several engineering applications with regards to the obtained parameters, the use of these parameters in the standard series IEC 62305 and several IEEE standards for instance are mainly based on the direct measurements by Bergerand co-workers in Switzerland. Meanwhile more recent direct current measurements were obtained from instrumented towers in Austria, Germany, Russia, Canada and Brazil, as well as from rocket-triggered lightning. Further, modern lightning locating systems (LLS) report peak currents estimated from measured electromagnetic field peaks. ■