Parameters of Lightning Strokes and Their Effects on Power Systems

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***Abstract* - A lightning stroke can generate transient overvoltage on an overhead line by (i) directly striking a phase conductor, (ii) directly striking a tower or shield wire causing backflash, and (iii) striking a nearby ground. All three types of transient voltages are directly proportional to the return-stroke peak current. In addition, voltages by (ii) depend upon the current front time, and those by (iii) depend upon the front time and velocity of the return-stroke current and on the cloud height. The energy of the lightning flash may exceed the thermal limit of the struck object causing thermal failure. The statistical variations of these lightning parameters are discussed.**

***Index Terms* -** Lightning parameters, lightning statistics, lightning transients

I. INTRODUCTION

Lightning damages a power apparatus in two ways: (i) it raises the voltage across an apparatus such that the terminals across the struck apparatus spark over causing a short circuit of the system or the voltage punctures through the apparatus electrical insulation, causing permanent damage. (ii) The energy of the lightning stroke may exceed the energy handling capability of the apparatus, causing meltdown or fracture.

A lightning flash generally consists of several strokes which lower charges, negative or positive, from the cloud to the ground. The first stroke is most often more severe than the subsequent strokes. Low current continues to flow between two strokes, thus increasing the total energy injected to the struck object.

The transient voltage from the lightning strike is generated by: (i) direct stroke and (ii) indirect stroke. For direct strike, it can strike an apparatus. In that case, the apparatus will be permanently damaged. Most often, lightning strikes the phase conductor of the power line. In that case, a traveling voltage wave is generated on the line; it travels along the line and is impressed across the terminals of an apparatus or most often the insulator between the phase conductor and the cross-arm of the tower at the end of the span. If the voltage is high enough, the insulator flashes over causing a short circuit of the system. Many overhead power lines are equipped with shield wires to shield the phase conductors. Even then, shielding failures occur when lightning bypasses the shield wires and strikes a phase conductor. When lightning strikes a tower, a traveling voltage is generated which travels back and forth along the tower, being reflected at the tower footing and at the tower top, thus raising the voltages at the cross-arms and stressing the insulators. The insulator will flash over if this transient voltage exceeds its withstand level (backflash). Even if lightning strikes a shield wire, the generated traveling voltage wave will travel to the nearest tower, produce multiple reflections along the tower, causing backflash across an insulator. When lightning hits the ground several hundred meters away from the line (indirect stroke), the electric and magnetic fields of the lightning channel can induce high voltage on the line for the insulators of the low-voltage distribution lines to spark over causing a short circuit of the system. Thus, assuming the lightning channel to be a current source, the transient voltages across the insulator of a phase conductor are generated in three ways: (i) lightning striking the phase conductor (shielding failure), (ii) lightning striking the tower or the shield wire (backflash), and (iii) lightning striking the nearby ground (indirect stroke). The severity of these three types of transient voltages is influenced by different lightning parameters.

The transient-voltage withstand level of a power apparatus is not a unique number. An apparatus may withstand a high transient voltage which has a short duration even it has failed to withstand a lower transient voltage with longer duration. This characteristic of the insulation is known as the volt-time or time-lag characteristic of the insulation. This is illustrated in Fig. 1. The volt-time characteristic of an apparatus will be different for different waveshapes of the applied transient voltage [1,2]. It is also polarity sensitive.

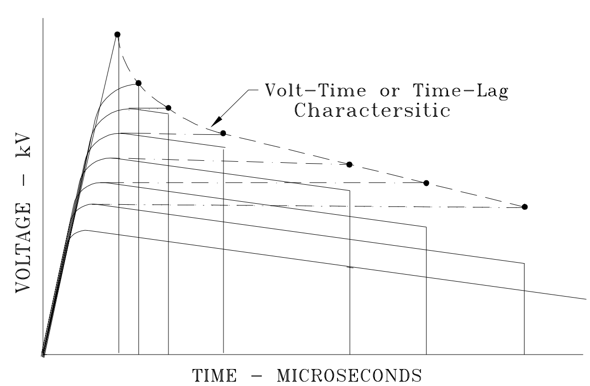

Fig. 1 Typical volt-time characteristic of insulation.

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Lightning being assumed to be a current source, the magnitude and shape of the return-stroke current wave play a significant role in the estimation of outage rates of power systems caused by lightning. The waveshape of a typical return-stroke current is shown in Fig. 2. The return-stroke current rises to its peak in a few microseconds and slowly decays after reaching the peak. The time to peak is called the front time, t_f, and the time duration from t=0 to the instant when the current subsequently decays to the 50 percent value of the peak is called the time to half value (tail time), t_h, and the current waveshape is called a t_f/t_h-μs wave. The time to half value, t_h, being many times longer than t_f does not play a significant role in the severity of lightning-caused transient overvoltages. However, the influence of the peak of the current wave, I_p, and t_f is very significant.

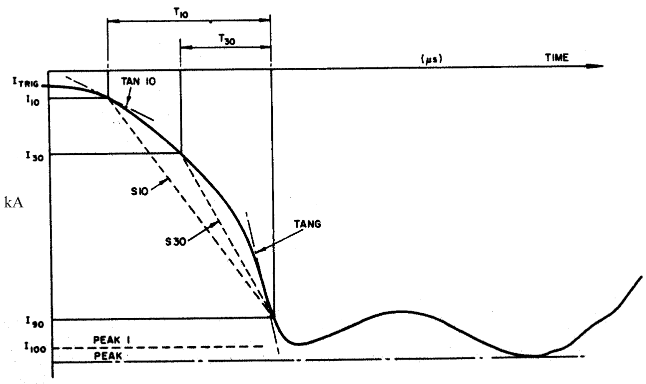


Fig. 2 Typical lightning return-stroke current wave.

II. SIGNIFICANCE OF LIGHTNING PARAMETERS

The significance of lightning parameters on power systems is gauged by the severity of the transient overvoltages they create and the consequent damages to the power system. As mentioned before, these overvoltages are generated by three different ways. These are discussed below.

A. Direct Stroke to Phase Conductor or Shielding Failure

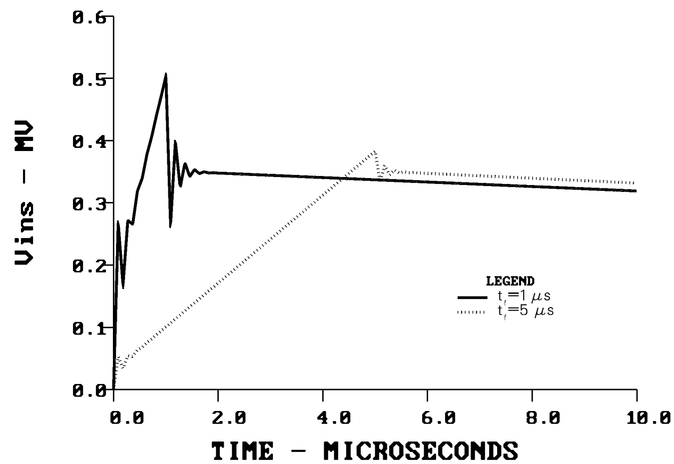
If lightning hits a phase conductor directly, the associated current, I(t), splits into two equal halves which travel in both directions along the struck phase conductor. The associated traveling voltage wave is given by:

$$V(t) = 0.5 I(t) Z_p, \qquad (1)$$

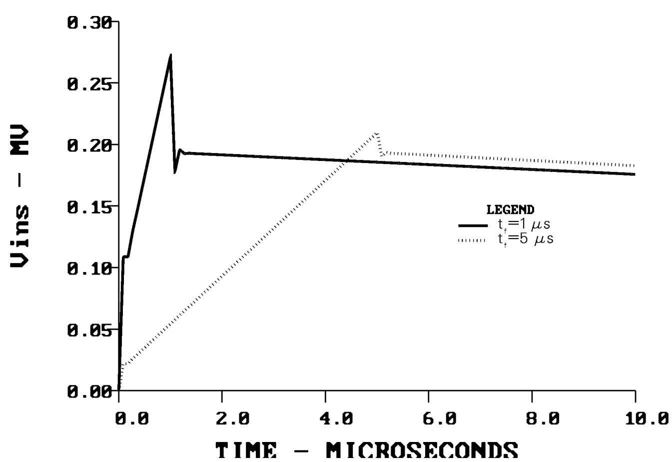
where Z_p is the phase-conductor surge impedance, given by $Z_p = \sqrt{L/C}$, and L and C are the series inductance (H/m) and capacitance to ground (F/m) per meter of the phase conductor. This voltage will be impressed across the insulator at the end of the span. The voltage will have the same waveshape as that of I(t), and the volt-time characteristic will be determined by this waveshape.

B. *Backflash*

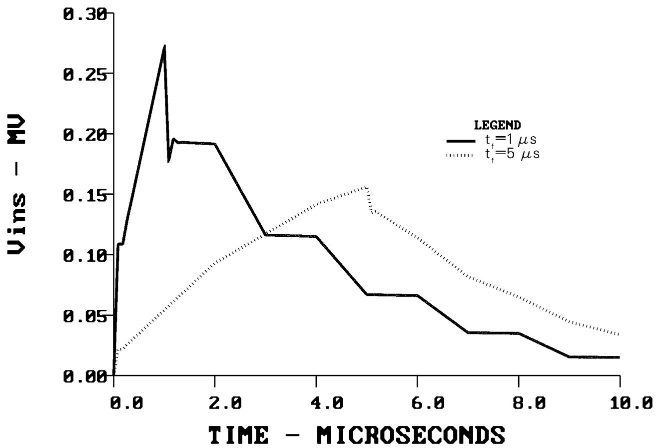
Backflash voltages are generated by multiple reflections along the struck tower and also along the shield wire for shielded lines at the adjacent towers. The backflash voltage across the insulator of the struck tower is not as straightforward as (1). The peak voltage will be directly proportional to the peak current. The shorter the front (t_f) the higher will be the voltage before the negative reflections from the tower footing along the tower and from the adjacent towers along the shield wire come back to the cross-arm to relieve the cross-arm voltage. The tail time, t_h, has much less influence on the waveshape of the backflash voltage because the superposed negative reflections completely distort the wavetail of the backflash voltage. Three illustrations are shown in Fig. 3.



(a) No shield wire



(b) One shield wire (reflections from adjacent towers neglected)



(c) One shield wire (reflections from adjacent towers considered)

Fig. 3 Insulator voltage for lightning strike to tower/shield wire [3].
Tower height=11 m; cross-arm height=10.5 m; phase-conductor height=10 m
Tower surge impedance=100 Ω; lightning-channel surge impedance=500 Ω
Return-stroke current=1/50-μs and 5/50-μs 30 kA

C. *Voltage Induced by Strokes to Nearby Ground*

The voltage induced on a phase conductor by lightning stroke to a nearby ground is significantly influenced by the following lightning parameters: (i) return-stroke current, (ii) front time of the return-stroke current, t_f, (iii) return-stroke velocity, and (iv) cloud height.

As with the other two types of lightning-generated voltages, the induced voltage is directly proportional to the magnitude of the return-stroke current. The dependence on the other lightning parameters is more complex. Typical examples of the dependence on the front time and velocity of the return-stroke current are shown in Figs. 4 and 5. In Fig. 5, β is the per-unit return-stroke velocity.

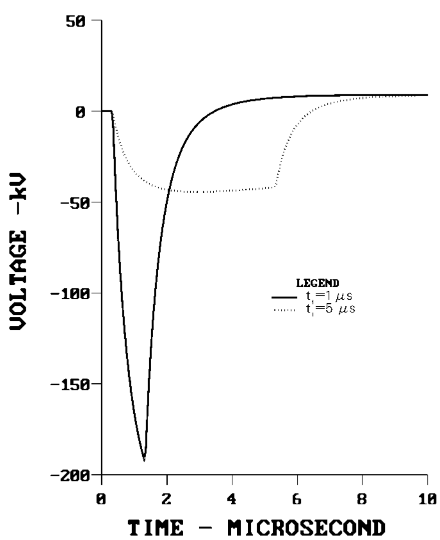


Fig. 4 Effect of t_f on phase-conductor induced voltage [4].
Line height=10 m; lateral distance of stroke from line=100 m

Return-stroke current=-30 kA; return-stroke per-unit velocity=0.3

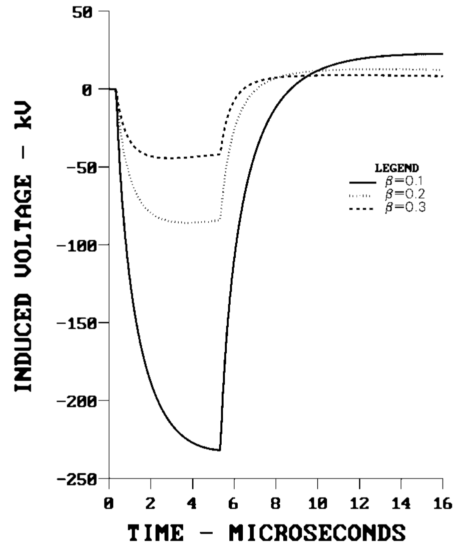


Fig. 5 Effect of β on phase-conductor induced voltage [4].
Return-stroke front time=5 μs; per-unit return-stroke velocity=0.1, 0.2, 0.3
Other parameters same as in Fig. 4

III. STOCHASTIC NATURE OF LIGHTNING PARAMETERS

No two lightning are the same, so are their parameters. Therefore, the statistical distribution of these parameters need to be known from many measurement data points. Lightning parameters have been measured, directly and indirectly, in many regions of the world. Lightning current has been measured directly by installing current-viewing resistor or current transformer on a tall tower which is frequently hit by lightning. Lightning current has been estimated indirectly by measuring the radiated electromagnetic fields of distant lightning. Both methods are subject to significant error.

Ground flash density, n_g, (number of lightning flashes to ground per km^2 per year) is a very important lightning parameter; lightning-caused outage rate of a power system is directly proportional to n_g. Ground flash density maps of various regions around the world are available to estimate the lightning-caused outages on power lines traversing through these regions. However, n_g varies seasonally, being higher generally during summer.

It is generally agreed that the statistical distribution of lightning return-stroke parameters follows the log-normal distribution, i.e., the statistical distribution of the logarithm of the variable follows normal (Gaussian) distribution. The probability density function, p(x), and the cumulative probability, $P_c(x)$, of a variable, x, are given as [3]:

$$p(x) = \frac{e^{-u^2}}{\sqrt{\pi}\,x}, \ \ and \ \ P_c(x) = 0.5erfc(u) \qquad (2)$$

where $u = \frac{\ell nx - \ell nx_m}{\sqrt{2}\sigma_{\ell nx}}$, x_m=median value of x, $\sigma_{\ell nx}$=standard deviation of ℓnx, and erfc(u) is complementary error function of u. Therefore, x_m and $\sigma_{\ell nx}$ need to be known to estimate the statistical distribution of a lightning parameter.

Berger collected lightning data (1947-1971) from direct measurements on a 70-m tower on the top of Mount San Salvatore near Lugano, Switzerland [5]. Berger's data were comprehensively analyzed in [6-9]. The summary of this analysis is shown in Table I.

The return-stroke velocity affects only the voltage induced on a phase conductor by stroke to nearby ground (Fig. 5). We have analyzed data on return-stroke velocity from three groups of field tests [10-12]. The results are shown in Table II. An empirical equation relating the velocity, υ, to the peak current of the first negative stroke, I_p, is widely used which is shown in (3) [13,14]:

$$\upsilon = \frac{c}{\sqrt{1+\frac{500}{I_p}}} \quad \text{(m/s)} \qquad (3)$$

where c=velocity of light in free space and I_p=peak return-stroke current in kA.

If the energy in a lightning flash exceeds the thermal limit of the struck object, it results in a thermal runaway condition (e.g., melting of shield wire, puncture of surge protector blocks, etc.). The energy in a lightning flash is assessed generally by its charge, Q, and by $\int i^2 dt$. These are shown in Table III.

Table I: Statistical Parameters of First and Subsequent Negative Return-Stroke Currents [6-9]

Parameter x	Negative First Stroke		Negative Subsequent stroke		Positive Stroke	
	Median	$\sigma_{\ell nx}$	Median	$\sigma_{\ell nx}$	Median	$\sigma_{\ell nx}$
I_p, kA	61.1 for $I_p \le 20$ kA 33.3 for $I_p > 20$ kA	1.33 for $I_p \le 20$ kA 0.61 for $I_p > 20$ kA	12.3	0.53	35	1.21
T_{10}, µs	4.5	0.58	0.6	0.92		
T_{30}, µs	2.3	0.55	0.4	1.01	13.2	1.23
t_f, µs	3.83	0.55	0.67	1.01	22.0	1.23
t_h, µs	75.0	0.58	32.0	0.93	230	1.33
S_{10}, kA/µs	5.0	0.64	15.4	0.94	-	-
S_{30}, kA/µs	7.2	0.62	20.1	0.97	-	-
S_m, kA/µs	24.3	0.60	39.9	0.85	2.4	1.54

Note 1: T_{10} is time interval between the 10 % (I_{10}) and 90% (I_{90}) of the current peak on the current wavefront, $T_{10}=t_{90}-t_{10}$ $T_{30}=t_{90}-t_{30}$; t_f (effective front time)=$T_{30}/0.6$; $S_{10}=(I_{90}-I_{10})/T_{10}$; $S_{30}=(I_{90}-I_{30})/T_{30}$; S_m=max. current rate of rise on wavefront
Note 2: trigger level=2 kA

Table II: Statistical Parameters of Negative Return-Stroke Velocity [10-12]

Stroke Type	Source	Sample Size	Mean Velocity (m/µs)	Sample Standard Deviation (m/µs)
First	Ref. 10	7	42.71	21.20
	Ref. 11	4	52.50	30.67
	Ref. 12	12	88.08	38.14
	Composite	23	68.09	38.01
Subsequent	Ref. 13	29	36.0	15.11
	Ref. 14	9	77.11	21.02
	Ref. 15	38	105.29	32.72
	Composite	76	75.51	41.40

Table III: Statistical Parameters of Stroke/Flash Charge and $\int i^2 dt$ [5]

Stroke/Flash	Charge, Q		$E=\int i^2 dt$	
	Q_m (C)	$\sigma_{\ell nQ}$	E_m (kA^2s)	$\sigma_{\ell nE}$
Negative first stroke	5.2	0.93	-	-
Negative subsequent stroke	1.4	1.25	-	-
Total negative flash	7.5	1.02	5.5×10^4	1.4
Total negative subsequent strokes	-	-	6×10^3	1.31
Positive stroke	16	1.36	-	-
Positive flash	80	0.90	6.5×10^5	1.91

IV. DISCUSSION

Table I shows two values for the median negative first stroke current: 61.1 kA for $I_p \leq 20$ kA and 33.3 kA for $I_p > 20$ kA. A mean value of the median current, 30.1 kA with $\sigma_{\ell n I p} = 0.76$, has been suggested [8]. This essential parameter of the lightning stroke has been the topic of much debate. It has been shown by several investigators that the median value of the return-stroke current is a function of the height of the struck object. Mousa and Srivastava suggest that the median value of the negative first stroke current on overhead power lines should be about 30 kA and that for stroke to flat ground about 24 kA with $\sigma_{\ell n I p} = 0.76$ for both cases [15].

Errors in the measurement of return-stroke currents should also be borne in mind. For direct measurement on tall towers, the reflections at both ends of the struck tower will contaminate the current waveshape. For indirect measurement, the peak of the current is estimated by measuring the radiated magnetic field of the lightning stroke, assuming the transmission-line model of the lightning stroke for a lossless earth [16]:

$$I_{peak} = -\frac{2\pi\varepsilon_o c^2 D}{\upsilon} E_{peak}\,, \; and \;\; E_{peak} = cB_{peak} \qquad (4)$$

where D =distance of the stroke from the antenna. Several errors are encountered in this method of measurement: (i) the return-stroke velocity is a function of the peak current; therefore, the assumption of a constant velocity is incorrect; (ii) several models of the return stroke have been proposed; none has been accepted as superior to the others; (iii) for nearby strokes, the assumption of the radiation field is not acceptable; (iv) even when the stroke is distant, the radiated field is attenuated when it reaches the antenna, the attenuation being a function of the ground resistivity.

The disparity in the mean velocities among the three groups of investigators in Table II should be noticed, even though the basic measurement techniques for all of them are similar, e.g., Boys camera, streaking camera. As the sample sizes are small for all three groups, the sample mean may not represent the population mean. In [12], the data taken in Florida and in New Mexico in two consecutive years show the mean velocities to be 66 m/μs and 150 m/μs, respectively for the first negative stroke. In Table II, these two means were averaged. It leads to the suggestion that (i) lightning parameters are different for different regions of the world, and (ii) these parameters could vary significantly from year to year for the same geographical region.

V. CONCLUSIONS

1. The most significant parameters of the lightning return stroke to estimate the severity on the power system are: (i) peak current, (ii) current front time, (iii) velocity and (iv) total charge of the flash.
2. Better techniques for the measurement of lightning parameters should be developed and standardized.
3. The global parametric data as used now may not be adequate. Regional data should be developed for better estimate of lightning-caused severity on power systems.

VI. ACKNOWLEDGMENT

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