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FRONT DURATION AND CURRENT STEEPNESS OF LIGHTNING STROKES TO THE EARTH

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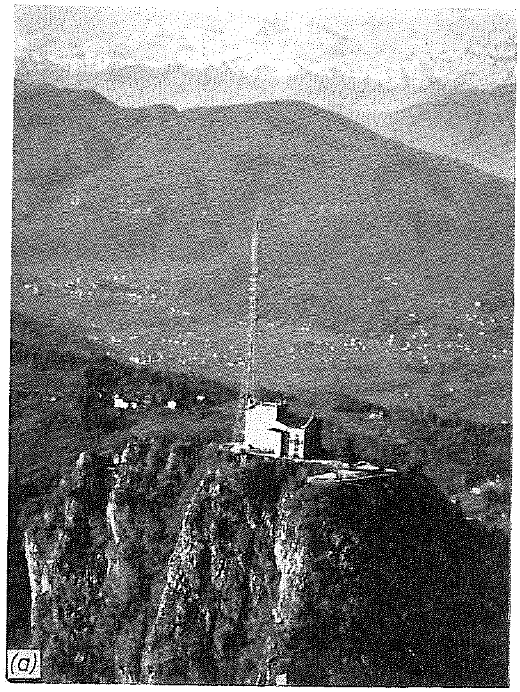
During the years 1958–1961, at the base for lightning research on Monte San Salvatore, near Lugano, four types of lightning currents could be distinguished. One of them seems to occur only on high and steep mountains as well as on very high buildings or towers in connection with upward leaders. The other three types occur not only on mountain tops but also in the plains. Of these, two are produced by the discharge of negative clouds and the third by the discharge of positive clouds to earth. While it is well known that there is a marked difference in the number of partial strokes or components between both polarities, the four types mentioned also show a marked difference in the current curves, especially with regard to front time and front steepness of partial strokes. Only the three latter types of current are dangerous to the transmission of electric power. Examples of these three current types are given and discussed in this paper.

Measuring equipment

THE whole installation for lightning research on Monte San Salvatore was described in the Bulletin of the Swiss Institution of Electrical Engineers in 1955.[1] At the beginning of 1958, a new cathode-ray oscillograph (c.r.o.), especially developed for the measurement of lightning currents, was installed. The examples of lightning current curves given in this paper were taken with this new c.r.o. In a few words, the measuring equipment consists of two lightning towers each 70 m high and at about 400 m horizontal distance. Tower 1 is situated about 15 m below the top of the mountain. This tower was erected in 1958 by the Swiss PTT to serve as a television tower. It stands on the site of the wooden lightning tower described in reference 1. *Figure 1* shows this television tower with the insulated lightning conductor and the lightning current shunt on top. Tower 2 is situated on a lower site on the mountain called Monte San Carlo, and was erected exclusively for lightning research (*Figure 2*).

The summit of Monte San Salvatore is 640 m above the level of the lake of Lugano and 915 m above sea level. The top of Tower 1 is about 695 m above lake level and the top of Tower 2 is about 650 m above the lake. The lightning towers are connected to the measuring station, placed in an old building, by polyethylene cables 120 and 500 m in length. These cables are of special construction to provide sufficient screening during lightning strokes. The circuit for measuring lightning currents is shown in *Figure 3*.



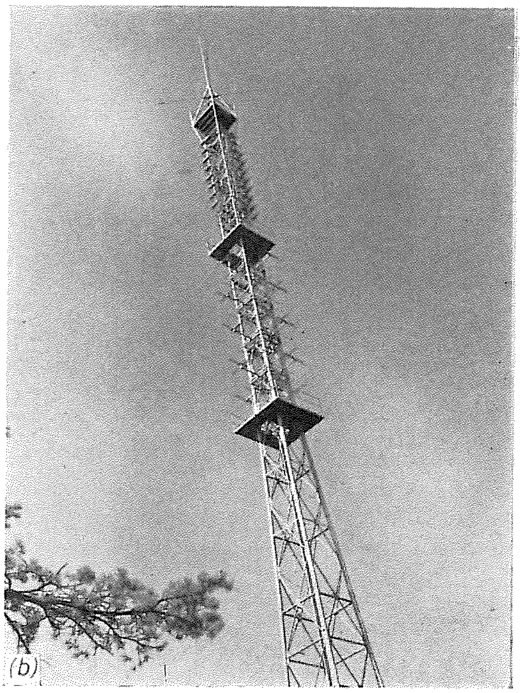


Figure 1. Television tower T_1 on Monte San Salvatore, built in 1958, with lightning conductor and measuring shunt on top of tower; (*a*) general air view from east to west (Monte Rosa at 80 km distance); (*b*) upper part of tower

For each tower a double-beam c.r.o. indicates the voltage drop on a tubular shunt R_1 of 0·05 ohm on two different current scales. At the c.r.o. end of the measuring cables there is a high-frequency resistor which serves at the same time as a matching resistor and as a voltage divider for both oscillographs, i.e. c.r.o. and electro-magnetic oscillograph (e.m.o.).

Tripping is effected primarily by small lightning currents sparking across

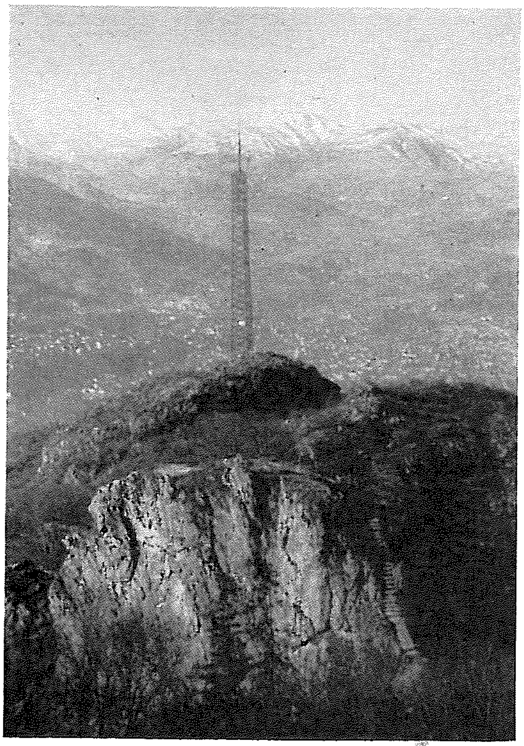


Figure 2. Lightning research tower T_2 on Monte San Carlo, built in 1950 400 m from peak of San Salvatore, with lightning conductor and shunt-platforms on top

the gap F. This causes the inscription of the oscillogram on a slowly moving film or paper, rotating on a drum at a speed of 1 m/sec. This mechanical time base is accompanied by an electric time base moving the cathode ray in the same direction at high speed, i.e., at 30/100 μsec or 200/1,000 μsec to and fro using a flip-flop current. Tripping of this high-speed deflection is caused by fast current variations of about 1 kA/μsec with about 1 μsec delay. Since 1960 delay cables have been used to compensate for this delay. The fast to-and-fro time deflection being over, tripping again is possible without delay.

Each tower (T_1 and T_2) is connected to two c.r. beams with independent time and current scales. During 1958 and 1959 one beam was used with a high current sensitivity of about 50 A/mm. Since 1960 both beams have been used with low current sensitivities of about 2 and 6 kA/mm. The lower current is combined with the fast time base (30/100 μsec) and the higher current range with the 200/1,000 μsec time base. It is thus intended to get the maximum information on current/time curves.

The new c.r.o. was developed on the basis of our lightning measurements since 1943. It was constructed by Dr. P. E. Klein at Tettnang, Bodensee, Germany. Precision of measurement is limited by the damping in the polyethylene cables and by the response time of the shunt R_1. Since 1943,

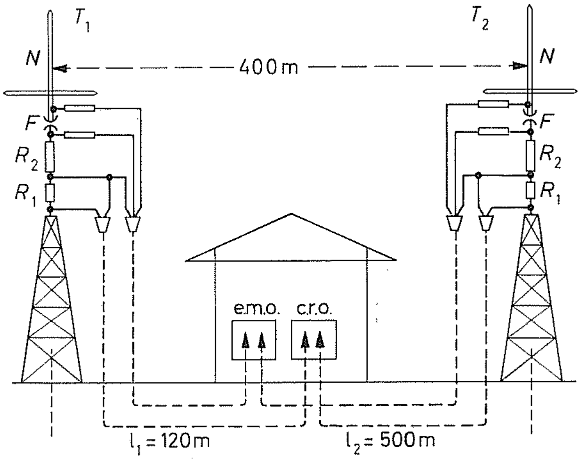


Figure 3. Principal diagram of the circuit for the measurement of lightning currents

T_1 and T_2: lightning towers
N: insulated lightning conductor
F: Small air gap for tripping circuit and for permanent measurement of corona current, 'St. Elmo's Fire'
R_2: Shunt resistor of 0·75 ohm for low frequency currents
R_1: Tubular resistor of 0·05 ohm for impulse currents
c.r.o.: Cathode ray oscillograph
e.m.o.: Electro-magnetic oscillograph

we have used a multiple tubular shunt of constantan (formerly cumal) with a response time of 50 nsec (0·05 μsec). The shunt is designed for lightning currents of 200 kA amplitude and 200 μsec duration. This type of shunt has been approved by Technical Committee 42 of the IEC.[2]

Frequency of lightning stroke oscillograms on Monte San Salvatore from 1958 to 1961

Table 1 shows the figures for strokes to Towers 1 and 2 which produced oscillograms.

Table 1. Strokes producing oscillograms

Lightning season	*Negative strokes*	*Positive strokes*	*Bipolar strokes*
1958	7	—	1
1959	54	5	2
1960	33	8	—
1961	18	—	—
1958–61	112	13	3

A negative or positive stroke is defined as the discharge to earth of a negative or positive cloud. A bipolar stroke begins with a negative charge to earth, changes to positive and sometimes returns to negative.

Lightning-current types

Type A

This type occurs when a leader stroke is progressing upwards from the top of a tower towards a charged cloud. It is observed only on very high

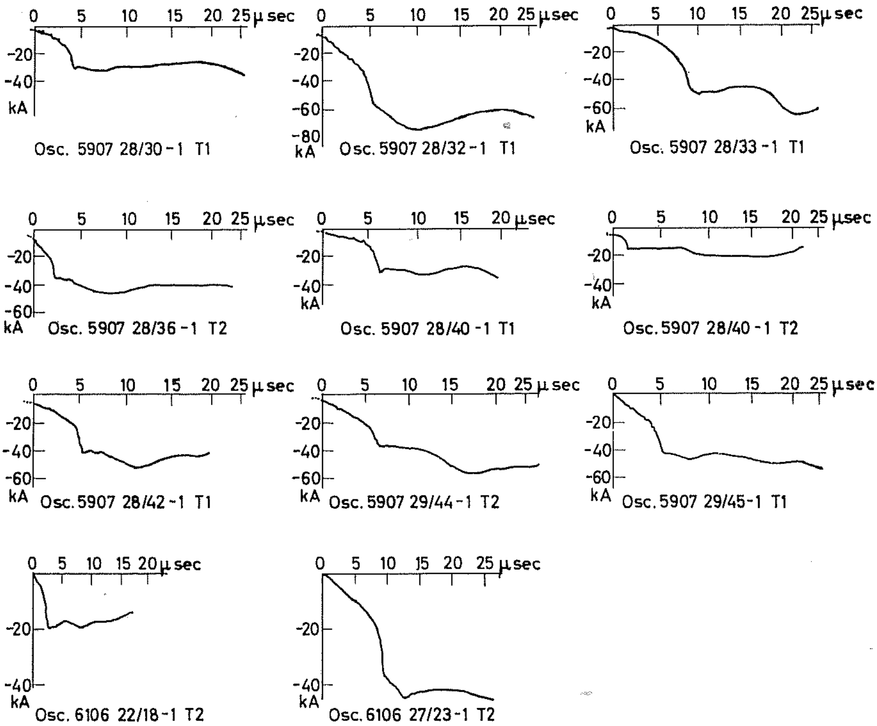


Figure 4. Current-type B, examples 1959 to 1961. First strokes with downward leaders from negative clouds to earth

buildings, such as the Empire State Building,[3] or on the top of high and steep mountains like San Salvatore where half of all strokes are of this type. The current curve is characterized by a very slow front rise and current amplitudes between 20 A and several 100 A. The duration is between some hundredths and some tenths of a second. The electric charge is several Cb up to about 30 Cb. The accounts of many examples of currents of this type have been published.[1] Their influence on power transmission is generally negligible, therefore we shall not discuss them here.

Type B

This type is caused by the first downward progressing leader from a negative cloud when it approaches the earth and releases the first partial main stroke. This may include the formation of an upward midgap streamer from a tower. *Figure 4* shows some examples of current curves of this type obtained during the lightning seasons of 1959 to 1961. *Table 2* gives the results of the evaluation of these oscillograms regarding amplitude, front duration (IEC), front steepness (IEC) and maximum steepness $(di/dt)_{max}$ or s_{max}. The current

Table 2. Type B

Stroke number(1)	*Tower 1 or 2*	i_{max}(2) (kA)	T_F IEC(3) (μsec)	s_{IEC}(3) (kA/μsec)	s_{max} (kA/μsec)
590728/30-1	T_1	−33	4	8·1	24
590728/32-1	T_1	−74	9·6	7·7	21
590728/33-1	T_1	−49	7	7·0	15
590728/36-1	T_2	−45	5·6	8·0	28
590728/40-1	T_1	−33	7·2	4·5	16
590728/40-1	T_2	−15	4	3·8	21
590728/42-1	T_1	−52	11·6	4·5	25
590729/44-1	T_1	−38	6·8	5·5	18
590729/45-1	T_1	−47	5·4	8·7	20
610622/18-1	T_2	−22	3·4	6·5	17
610627/23-1	T_2	−44	10·2	4·3	11

(1) The 'Stroke number' is composed of:
(*a*) Two digits for the year, i.e. 59 for 1959
(*b*) Two digits for the month, i.e. 07 for July
(*c*) Two digits for the day, i.e. 26 for the 26th
(*d*) Number of oscillogram and partial stroke, i.e. 18 − 1 for first partial stroke of oscillation 18
(2) The value i_{max} is measured at the first peak leading to a more or less constant tail of the current curve. Slow current rises after 10 to 15 μsec are not taken into account. Therefore, i_{max} is not identical in all cases with the real maximum of current
(3) Front time (rise time) T_F and steepness s_{IEC} are defined by the straight line through the points 10 per cent and 90 per cent i_{max} of the current curve; where the beginning of the i-curve is above 10 per cent i_{max}, the curve is extrapolated down to 10 per cent i_{max}
T_F: front duration corresponding to the IEC definition
s_{IEC}: steepness corresponding to the IEC definition, i.e. i_{max}/T_F
s_{max}: maximum steepness between 2 points of 0·1 i_{max} interval

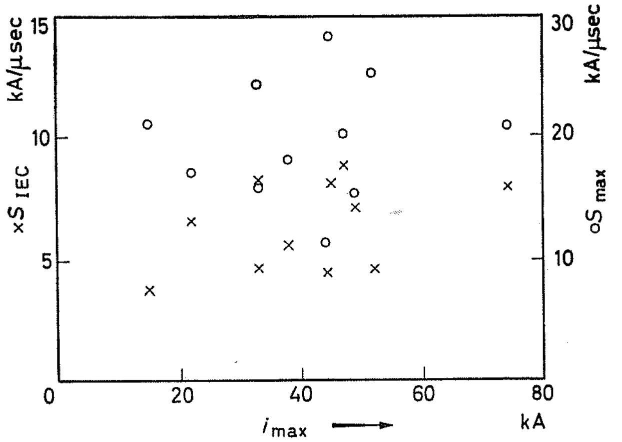


Figure 5. Correlation between current-steepness, s, and current-amplitude i_{max}

s_{IEC}, s_{max} } see *Table 2*

curves are concave, i.e. maximum steepness occurs at the end of the rise of current where a sharp bending leads generally to the current tail. This observation has already been made in an earlier publication[1] where a c.r.o. with cold cathode was used. The concave curve causes a very pronounced difference between the steepness calculated by the two definitions (IEC and s_{max}).

Figure 5 is designed to reveal whether any correlation exists between amplitude and steepness of this current type. There is a small tendency for rising s_{IEC} values with current amplitude from about 5 to 8 kA/μsec in the visible current range (15–75 kA). But no correlation seems to exist between s_{max} values and current. s_{max} is always between 10 and 30 kA/μsec. It is not the object of this paper to discuss the extremely interesting problem of the formation of the lightning spark to which these observations may contribute.[4]

Type C

This current type is caused by the subsequent partial strokes from negative clouds. The subsequent strokes are always initiated by downward dart leaders which travel at a much higher speed than the first stepped leader, which is often very difficult to photograph. *Figure 6* shows some examples of current curves of type C. *Table 3* gives figures on amplitude, front time and steepness for the oscillograms in *Figure 6*.

Table 3. Type C

Stroke number	*Tower 1 or 2*	i_{max} (kA)	T_F IEC (μsec)	s_{IEC} (kA/μsec)
590728/33-2	T_1	−30	≤1·1	≥27[2]
590728/33-4	T_1	−25	≤1·1	≥22[2]
590728/33-6	T_1	−17	≤1·1	≥15[2]
590728/33-7	T_1	−35	≤1·1	≥31[2]
590728/33-8	T_1	−18	≤1·1	≥16[2]
590728/33-9	T_1	−28	≤1·1	≥25[2]
590728/40-3	T_1	−20	≤1·1	≥18[2]
590728/40-5	T_1	−28	≤1·1	≥25[2]
590728/40-6	T_1	−15	≤1·1	≥13[2]
590729/44-2	T_1	−12	≤1·1	≥11[2]
590729/45-3	T_1	−14	1·1	≥13[2]
590729/45-4	T_1	−23	1·1	21[2]
600812/19-2	T_2	−11	≤1	≥11[2]
600904/26-2	T_2	−8	0·6	13
610515/5-2	T_1	−10	0·8	12·5
610609/9-2	T_2	−11	0·7	15
610609/9-3	T_2	−6	ca. 0·3[1]	20[1]
610609/10-2	T_2	−9	1	9
610812/25-2	T_2	−9	1·3	7·3

(1) These values of T_F and s are doubtful because of the greater tripping delay with the small amplitude of 6 kA
(2) In 1958 and 1959 no delay cables were used. Since 1960 delay cables of 1·75 μsec delay were introduced. The delay time of the tripping circuit was then found to have been less than 1·1 μsec in 1959. Therefore, only minimum values of s can be given for 1959 and the spring of 1960
(3) Stroke number
T_F, s_{IEC} } see *Table 2* notes numbers (1) and (3)

The great number of subsequent strokes measured between 1958 and 1961 confirm and extend the former results which show much shorter front duration for all subsequent strokes than for the first partial stroke. The wave-form of subsequent strokes is astonishingly regular in front and tail and without any pronounced ripples, no matter whether the first stroke was of type A or B.

The front duration of subsequent strokes can only be measured with the help of delay cables. When no delay cables were used, as in 1958 and 1959, the front of the current curve was never visible. Since the use of delay cables of 1·75 μsec delay time in 1960, it has been possible to show that the tripping

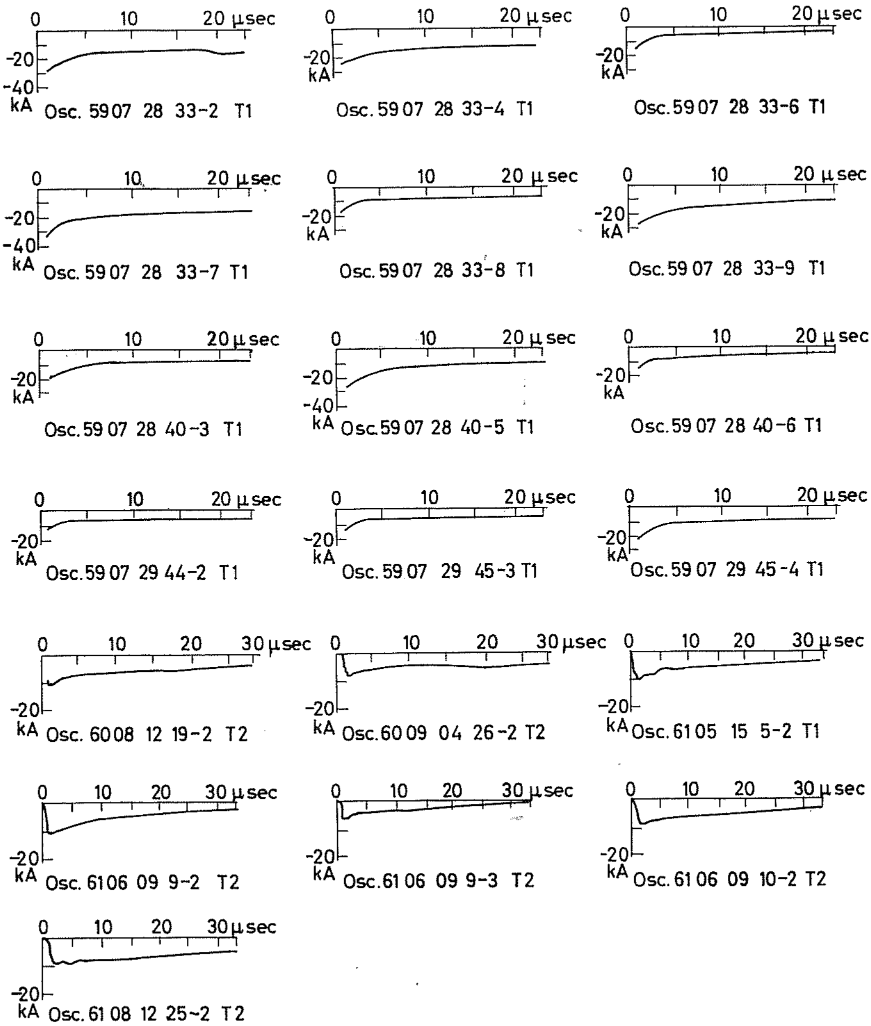


Figure 6. Current-type C, examples 1959 to 1961. Subsequent strokes from negative clouds to earth

delay was about 1·1 μsec. Therefore in 1959, the values of front time T_F and steepness s in *Table 3* are maximum and minimum values respectively and exact values could be obtained only in 1960 and 1961. The front time is always near 1 μsec or less, independent of current amplitudes. The measuring cables and delay cables have a frequency range of up to 15 Mc/sec. Therefore it may be concluded that the front time of type C currents is generally less than 1 μsec.

The shape of the current curve is approximately that of an IEC-impulse. The difference between IEC-steepness and s_{max} is not important and is much smaller than in type B currents. The fast time scale of the oscillograms does not enable exact s_{max} values to be measured. These may be 50 to 100 per cent higher than the s_{IEC} values of *Table 3*. By comparing the steepness-values of *Table 3* with the s values of *Table 2* it is evident that the s_{IEC} values of *Table 2* are always smaller than those of *Table 3* notwithstanding the greater current amplitudes in the first partial stroke. But the s_{max} values of *Table 2* do not differ significantly from the steepness values of *Table 3*. This means that the steepness at the end of the concave front of the first partial stroke s_{max} is about the same as the mean

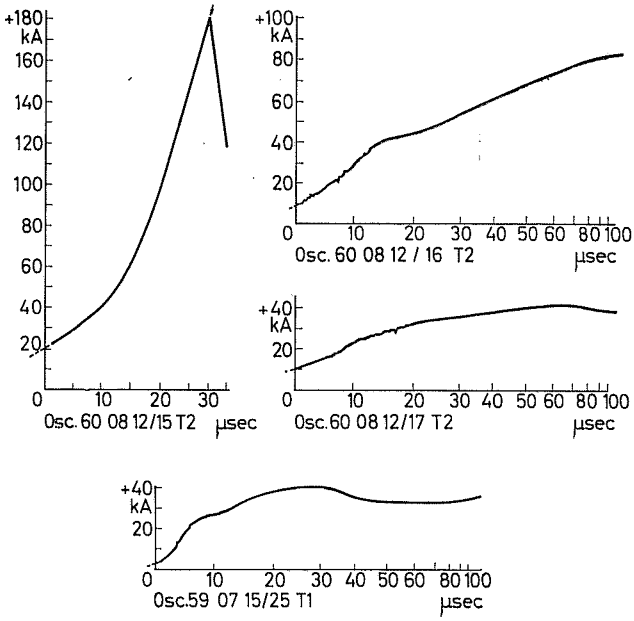


Figure 7. Current-type D, examples 1959 to 1961. Strokes from positive clouds to earth

steepness of the subsequent strokes. The same data on front times can be expressed as follows: Front time (IEC) is between 3 and 12 μsec for current-type B and 1 μsec or less for current-type C.

Type D

This type of lightning current is connected with the discharges to the earth of positively charged clouds. Contrary to the discharge of negative clouds, positive clouds discharge, with very few exceptions, in a single stroke. *Figure 7* shows some examples of positive strokes, i.e. discharge currents of positively charged clouds. Their evaluation is given in *Table 4*. From these examples it can easily be gathered that the current curves differ very much from types B and C. Front duration is much longer than for types B and C. The concave shape which is so characteristic of type B can, in general, not be seen here. The mean value of the electric charge of positive strokes is greater than the sum of all partial stroke charges of types B and C in a complete negative stroke. Charges of more than 100 Cb are not infrequent. The duration of type-D strokes is normally from one to a few hundredths of a second without interruption. During this time, amplitudes of several kA are attained but rarely more than 30 kA.[1]

Table 4. Type D

Stroke number	*Tower 1 or 2*	i_{max} (kA)	T_F IEC (μsec)	s_{IEC} (kA/μsec)	s_{max} (kA/μsec)
600812/15[1]	T_2	+180	36	5·0	9
600812/16	T_2	+82	90	0·9	2·2
600812/17	T_2	+42	71	0·59	1·8
590715/25[2]	T_1	+41	20	2·05	4·1

Tripping of the fast oscillogram is caused by current variation (di/dt). Therefore, the first part of the record may be lost if the beginning of the front is very flat (1 kA/μsec or less). This applies especially to positive strokes.

(1) This 'giant stroke' caused a flashover on the shunt R_2, indicated by the sign ϟ in *Figure 7*

(2) This positive stroke belongs to a bipolar discharge with a negative–positive–negative sequence of components

(3) T_F, s_{IEC}, s_{max} } see *Table 2*

Sometimes, i.e. about every 5 to 10 years, exceptionally strong discharges of type D are observed on Monte San Salvatore. In the previous stage of research the current measuring shunt R_2 (*Figure 3*) was destroyed by these 'current-giants'. The last observation of this sort was made in 1960, when stroke No. 15 in *Figure 7* caused a mechanical and thermal overstress of shunt R_2 (1 ohm with 25 kg of constantan). Since then, the thermal capacity of R_2 has been tripled, and the measured mechanical strength by even more, with a new 0·75 ohm-shunt. For these three 'giants' of *Figure 7*, Nos. 15, 16 and 17, the value $\int i^2\, dt$ is about $(2–4) \times 10^6$ A^2sec. This is several times the maximum value for the negative currents of types B and C measured since 1945. The present paper is not the place to discuss the reason for the severity of type-D currents. It is quite possible though that the explanation for the single-stroke mechanism lies at the bottom of a more complete discharge of positive clouds to the earth.

Short discussion on current types and lightning protection

Three factors which are of primary importance for lightning protection are given below:

(*a*) The ohmic voltage drops caused by lightning currents, especially in earthing devices for lightning.

(*b*) The inductive voltage drops in conductors charged by lightning currents, or the induced voltages in nearby conductors.

(*c*) The section or size of lightning current conductors.

As to (*a*), current-type D would cause the most severe ohmic drops. Tower footing resistances and earthing resistances of stations sufficient to support heavy currents without back flashover cannot always be realized economically.

On the other hand, ohmic voltage drops on metallic lightning conductors generally are not important if these conductors are thermally and mechanically adequate (see (*c*) above).

Factor (*b*) is of major importance when discharges from a lightning conductor to other conducting objects are to be avoided. A wire with an inductance of about 1·5 μH/m shows an inductive voltage drop of

15 kV/m for a current variation of 10 kA/μsec or

45 kV/m for a current variation of 30 kA/μsec.

An insulated wire parallel to the lightning conductor may be exposed to this voltage when the far ends of the wire and the lightning conductor are bonded together and earthed.

Some national rules for lightning protection therefore ask for a minimum spacing of about 1/10 of the length of the parallel conductors to avoid flashovers between them. When the parallel conductor is not connected to the lightning conductor the voltage stress between them is about half of the above value. It may be concluded from this very simple and rough approximation that midspan lightning strokes of types B and C to the earth wire of a transmission line can sometimes cause flashover of insulators at the next tower, i.e. a stroke to midspan on a 300 m span may produce

$150\ \text{m} \times \frac{1}{2} \times 15\ \text{kV/m} \times \frac{1}{2} = 560\ \text{kV}$ at the next insulators for 10 kA/μsec current steepness or

$150\ \text{m} \times \frac{1}{2} \times 45\ \text{kV/m} \times \frac{1}{2} = 1{,}700\ \text{kV}$ for 30 kA/μsec current steepness.

As a further example, it can be deduced that in reinforced concrete buildings where a great number of vertical steel wires are used as lightning current conductors there is no danger of flashover to conducting objects inside the building. The grid of steel wires very nearly gives the effect of a complete Faraday cage, even against the steeper currents of types B and C.

With regard to factor (*c*) above, a copper wire of 10 mm^2 or a steel wire of 30 mm^2 section will just survive a current giant of type D with a value of $\int i^2\,dt = (4\text{–}6) \times 10^6\ \text{A}^2\text{sec}$. Experience of the lightning protection of buildings shows that a conductor of this size is very rarely damaged, and that if damage occurs it is only the joints or the points where lightning hits the earth wires that are affected, and not the whole of the conductor.

When taking into consideration only the results of the most frequent types of lightning, B and C, we were never able to really understand and explain extreme damage caused by lightning, but since taking into account lightning current of type D too, we can. Lightning is a meteorological phenomenon with a very wide dispersion in time and space and it is only by observations over long periods that we can hope to understand one of the most beautiful wonders of nature.

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