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Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequence
(Second Revision)

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Auspices
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<u>Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequence [Second Revision]</u>

Final Report on Grant B568621
to
Lawrence Livermore National Laboratory
from the
University of Florida
Department of Electrical and Computer Engineering
Principal Investigator: Martin A. Uman

J. O. Elismé, M. A. Uman, V. A. Rakov, and C. J. Biagi

Executive Summary

The University of Florida has surveyed all relevant publications reporting lightning characteristics and presents here an up-to-date version of the direct-strike lightning environment specifications for nuclear weapons published in 1989 by R. J. Fisher and M. A. Uman. Further, we present functional expressions for current vs. time, current derivative vs. time, second current derivative vs. time, charge transfer vs. time, and action integral (specific energy) vs. time for positive and negative first return strokes, for negative subsequent return strokes, and for positive and negative continuing currents; and we give sets of constants for these functional expressions so that the resultant waveforms exhibit approximately the median and extreme lightning parameters presented in the updated direct strike environment. Fourier transforms of the return stroke current waveforms are presented. The results of our literature survey are included in three Appendices entitled Return Stroke Current, Continuing Current, and Positive Lightning.

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I. Introduction

A lightning direct-strike environment specification for nuclear weapons was published over 20 years ago by R. J. Fisher of the Sandia Corporation and Martin A. Uman of the University of Florida in the document "Recommended Baseline Direct-Strike Lightning Environment for Stockpile-to-Target Sequences", May 1989, SAND-89-0192, Sandia National Laboratories, Albuquerque, NM. New information about lightning has become available in the past 20 years via measurements and analysis. As part of two LLNL grants, the University of Florida has surveyed all relevant publications reporting lightning characteristics and presents here an up-to-date (second revision) version of the 1989 direct-strike specifications. Information from UF's on-going program of measurement of the electromagnetic properties of close lightning, including the currents in triggered lightning strokes and the charge transfer in natural positive lightning, is, where appropriate, used to inform our judgments relative to the new specifications. Additionally, we present functional expressions for current vs. time, current derivative vs. time, second current derivative vs. time, charge transfer vs. time, and action integral (specific energy) vs. time for first positive and negative return strokes, for subsequent negative return strokes, and for continuing currents; and we give sets of constants for these expressions so that they yield approximately the median and extreme lightning parameters presented in this report. Expressions for representative median lightning waveforms are plotted. The following two sections (II and III) of this report deal with related aspects of the research: Section II. Recommended Direct-Strike Median and Extreme Parameters; Section III. Time-Domain Waveforms for First Strokes, Subsequent Strokes, and Continuing Currents. Results of the literature search used to derive the material in Section II are found in three Appendices: Appendix 1. Return Stroke Current, Appendix 2. Continuing Current, and Appendix 3. Positive Lightning.

II. Recommended Direct-Strike Median and Extreme Parameters.

An exact transcription of the direct-strike parameters recommended by Fisher and Uman (1989) (their Table 2) as the lightning environment to be used for stockpile-to-target sequences (STSs) for nuclear weapons is reproduced in Table 1. Fisher and Uman (1989) presented median (50%) values and extreme values (stated as "1% frequency of occurrence", but actually meaning that 1% of all events are expected exceed that value) for the parameters listed, and they noted that knowledge of the form of the probability distribution function along with these two values is sufficient to define the full distribution. They also note that 1% values should not be considered absolute extremes.

The probability distribution functions of some lightning parameters have been shown from measured data to be approximately log-normal (Uman, 1987, Appendix B3, pg. 339). Six important lightning parameters that have been demonstrated to follow the log-normal distribution to a reasonable degree of approximation are the negative first and subsequent return stroke peak currents, the charge transfer to 1 msec for negative first and subsequent return stroke currents, positive first return stroke peak current, and the time interval between negative strokes. Cianos and Pierce (1972), in a table reproduced in Uman (1987, Appendix B3), list 10 lightning parameters that they suggest can be described satisfactory by a log-normal distribution: flash duration, interstroke interval, return stroke peak current, flash charge transfer, time to return stroke current peak, rate of rise of return stroke current, time to return stroke current half-value, duration of continuing current, continuing current amplitude, and continuing current charge. Nevertheless, some of these parameters are only crudely approximated by the log-normal distribution and are certainly not described satisfactory enough by that distribution to allow adequate prediction of extreme values.

Table 2 contains our present recommendations for parameters comprising the direct-strike environment. Negative and positive strokes, negative and positive continuing currents, and negative and positive flashes are treated separately, in contrast to Fisher and Uman (1989) who combined parameters for negative and positive events.

Table 1

Recommended Direct-Strike Lightning Environment for Future STSs. Reproduced from Fisher and Uman (1989)

ABNORMAL LIGHTNING ENVIRONMENTS

A lightning strike directly to the warhead or to equipment associated with the warhead is considered a credible possibility. The lightning could be of either the cloud-to-ground or cloud flash (intracloud, intercloud, or cloud-to-air) type. Extreme (1% frequency of occurrence) and median (50%) values are given below for those cloud-to-ground flash parameters considered to constitute the most important threats to the weapon. Corresponding cloud flash parameters fall within the envelope defined below and are therefore not separately listed.

RETURN STROKE PARAMETERS[1]	1%	50%
a. Peak Current (kA)	200	30
b. Time to Peak (μs)	0.1-15	3
c. Max. Rate of Current Rise (kA/μs)	400	150
d. Time to Decay to Half Peak (μs)	10-500	50
e. Amplitude of Continuing Current[2] (A)	30-700	150
f. Duration of Continuing Current (ms)	500	150
FLASH PARAMETERS		
a. Number of Strokes	>20	4
b. Interstroke Interval (ms)	10-500	60
c. Total Flash Duration (ms)	30-1000	180
d. Total Charge Transfer (C)	350	15
e. Action Integral [$\int I^2 dt$] (A^2s)	3×10^6	5×10^4

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[1]The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as return strokes or, simply strokes.

[2]Continuing currents can occur between individual strokes, following the final stroke in a flash, or both.

Table 2
Direct-Strike Lightning Environment Recommended by the Present Study. Note That the 50% and 1% Columns are Reversed in Order from Table 1.

	50%	1%
RETURN STROKE PARAMETERS		
NEGATIVE FIRST STROKES		
(a) Peak Current (kA)	30	150
(b) Time to Current Peak (µs)	5	30
(c) Maximum Rate of Current Rise (kA/µs)	100	400
(d) Time to Decay to Half-Peak Value (µs)	70-80	300
(e) Charge Transfer (C)	5	40
POSITIVE FIRST STROKES		
(a) Peak Current (kA)	35	500
(b) Time to Current Peak (µs)	10-20	150
(c) Maximum Rate of Current Rise (kA/µs)	100	400
(d) Time to Decay to Half-Peak Value (µs)	†	†
NEGATIVE SUBSEQUENT STROKES		
(a) Peak Current (kA)	10-15	50
(b) Time to Current Peak (10-90 Percent) (µs)	0.3-0.6	9
(c) Maximum Rate of Current Rise (kA/µs)	100	400
(d) 10 to 90 Percent Rate of Current Rise (kA/µs)	30-50	150
(e) Time to Decay to Half-Peak Value (µs)	30-40	250
NEGATIVE CONTINUING CURRENT LONGER THAN 40 ms		
(a) Amplitude (A)	100-200	1000
(b) Duration (ms)	100	600
(c) Charge Transfer (C)	10-20	200
POSITIVE CONTINUING CURRENT		
(a) Amplitude (kA)	1	10
(b) Duration (ms)	85	1000
(c) Charge Transfer (C)	80	700
NEGATIVE FLASH PARAMETERS		
(a) Number of Strokes	3-5	25
(b) Interstroke Interval (ms)	60	600
(c) Duration (ms)	200	1000
(d) Charge Transfer (C)	20	200
(e) Action Integral (A^2s)	$8x10^4$	$3x10^6$
POSITIVE FLASH PARAMETERS		
(a) Number of Strokes	1	3
(b) Duration (ms)	85	1000
(c) Charge Transfer (C)	80	700
(d) Action Integral (A^2s)	$7x10^5$	$6x10^7$

† See discussion under Section II (e)

All parameters listed in Tables 1 and 2 represent lightning between the cloud and ground as observed near ground. The characteristics of intracloud or intercloud lightning are much less well studied than cloud-to-ground flashes but are thought to be generally less severe. Comparison of Table 1 and Table 2 shows that we have presented more lightning parameters than did Fisher and Uman (1989) and that some of the common parameters differ significantly. We comment below on the choice of the parameters listed in Table 2.

a. "Decay to 1000 A": As Fisher and Uman (1989) recommend, this parameter of Table 1 has been eliminated from Table 2.

b. Return stroke peak current: The peak current data in Table 2 for positive first strokes (rarely are there positive subsequent strokes – see Positive Flash Parameters in Table 2) and for first and subsequent negative strokes are taken from Berger et al. (1975) and their referenced previous work. The median (50%) values are relatively well established, and the 1% values are chosen from fitting log-normal distributions to the measured data, although some experimental data were measured near the 1% values of the data-fitting curve.

c. Maximum rate of return stroke current rise and other rise-time characteristics: In tower measurements such as made by Berger et al. (1975) this parameter is underestimated because of measurement system limitations and the potential influence of the strike object. Schoene et al. (2008) have shown that the strike object can affect rise-time parameters and that the highest rate of rise is for a well grounded object. The value of 100 kA/µs adapted as the 50% maximum rate-of-rise both for positive strokes and for negative first and subsequent strokes has been measured on well-grounded strike objects for negative strokes in triggered lightning, those strokes being similar, if not identical, to subsequent strokes in natural lightning (Schoene et al. 2008; Depasse 1994; Fisher et al. 1993). The inference that the same 50% maximum rate of rise of current characterizes negative and positive first strokes as is measured for negative subsequent strokes follows from the observation that the maximum rate of change of the remote electric field for the three types of strokes striking well-conducting salt water is essentially the same (e.g., Krider et al. 1996; Cooray et al. 1998). The 1% maximum rate-of-rise-time of 400 kA/μsec listed in Table 2 is near the largest value measured for a triggered-lightning return stroke, 411 kA/μs (Letienturier et al. 1991), and the largest value measured for lightning interaction with an aircraft in flight, 380 kA/μs (Pitts et al. 1987). Return stroke rise-time characteristics such as time to peak and 10 to 90% rise-time are determined from measured triggered-lightning current waveforms and tower current waveforms (primarily Berger et al. (1975) and the references therein) with comparison of the measured current characteristics to electric field and electric field derivative measurements for lightning over salt water being used to infer current characteristics not adequately measured directly.

d. Flash charge transfer: The charge transfer values in Table 2 are taken primarily from the experimental data of Berger et al. (1975) and a log-normal distribution fit to those measured data. For a positive flash, 700 C is inferred from the log-normal distribution fit as the 1% value, whereas the largest measured value from Berger et al. (1975) was 400 C at the 4% level. There have been a number of direct tower measurements of both positive and negative charge transfer between 300 and 1000 C for lightning in Japanese winter storms, with one positive charge transfer reported to exceed 3000 C (Miyake et al. 1992, Goto and Narita 1995). Positive charge transfers measured indirectly from remote magnetic fields by Li et al. (2008) and Lu et al. (2009) have a maximum value of roughly 2000 – 3000 C. The International Standard IEC 62305-1,3 (2006) lists 300 C as a "severe" charge transfer for all flashes.

e. Flash action integral: The values for action integral in Table 2 are taken from the data of Berger et al. (1975), references to their previous work given in that paper, and log-normal distribution extrapolations of those measurements. It is sometimes difficult to decide when a return stroke current ends and a continuing current begins, particularly for positive flashes which almost always exhibit large, long-duration variable currents following an initial current peak. If such long-duration currents are attributed to continuing current, then it is continuing current that makes the major contribution to the flash action integral value (and to the charge transferred). It follows that the "time to decay to half-peak value" is not well defined for positive first strokes. The International Standard IEC 62305-1,3 (2006) gives 10^7 A^2s for a "severe" first-stroke action integral, whereas we give 6 x 10^7 A^2s in Table 2 for the 1% value for a positive flash, consistent with the data of Berger et al. (1975).

f. Continuing current, negative and positive: Duration data for negative continuing current longer than 4 ms taken from the high-speed video measurements of Campos et al. (2007) indicate that 15 ms is at the 50% level and

550 ms is at the 1% level. Kitagawa et al. (1962) report, from electric field measurements, that half of all negative ground flashes exhibit continuing current intervals exceeding 40 ms. Kitagawa et al. (1962) term continuing currents exceeding 40 ms "long continuing current". In Table 2, we present data only for long continuing currents.

g. Other parameters: The best overall discussion of the parameters not discussed in (a) – (e) above, for which there would not be much argument and which are not particularly critical to induced or direct lightning effects, is found in Rakov and Uman (2003), which is also a source for further information on the parameters discussed above in (b) – (f).

III. Time-Domain Waveforms for First Strokes, Subsequent Strokes, and Continuing Current.

The time-domain functional expressions we present for various current related parameters are derived using the approach suggested by DeConti and Visacro (2007), following Heidler et al. (1999). Constants are chosen for these current-related expressions so that the waveforms approximate the various 50% parameters listed in Table 2. The resultant waveforms can be considered typical. The current-related waveforms can be altered by changing the constants found in the functional expressions. At the end of this section we will suggest constants to produce "severe" waveforms.

General: General functional expressions for the return stroke and continuing current waveforms are given below. There are four constants ($I0_k, n_k, \tau1_k, \tau2_k$) for each term in the summations. The constant $I0_k$ controls the amplitude, n_k controls the initial waveform steepness, $\tau 1_k$ is the front-time constant, $\tau 2_k$ is the decay-time constant, and η_k is termed the amplitude correction factor.

$$\text{Current: } i(t)=\sum_{k=1}^{m}\frac{I0_k}{\eta_k}e^{-\frac{t}{\tau 2_k}}\frac{\left(\frac{t}{\tau 1_k}\right)^{n_k}}{1+\left(\frac{t}{\tau 1_k}\right)^{n_k}} \tag{1}$$

with $\eta_k = e^{-\frac{\tau 1_k}{\tau 2_k}\left(n_k\frac{\tau 2_k}{\tau 1_k}\right)^{\frac{1}{n_k}}}$

$$\text{Current derivative: } i'(t)=\sum_{k=1}^{m}-\frac{e^{-\frac{t}{\tau 2_k}}\left(\frac{t}{\tau 1_k}\right)^{n_k}\left[t-n_k\tau 2_k+t\left(\frac{t}{\tau 1_k}\right)^{n_k}\right]I0_k}{t\left[\left(\frac{t}{\tau 1_k}\right)^{n_k}+1\right]^2\eta_k\tau 2_k} \tag{2}$$

Current second derivative:

$$i''(t)=\sum_{k=1}^{m}-\frac{e^{-\frac{t}{\tau 2_k}}\left(\frac{t}{\tau 1_k}\right)^{n_k}I0_k\left[n_k(\tau 2_k)^2-2t^2\left(\frac{t}{\tau 1_k}\right)^{n_k}-t^2-n_k^{\,2}(\tau 2_k)^2-t^2\left(\frac{t}{\tau 1_k}\right)^{2n_k}+2tn_k\tau 2_k\right]}{t^2\left[\left(\frac{t}{\tau 1_k}\right)^{n_k}+1\right]^3\eta_k(\tau 2_k)^2}+$$

$$-\frac{e^{-\frac{t}{\tau 2_k}}\left(\frac{t}{\tau 1_k}\right)^{n_k}I0_k\left[\left(\frac{t}{\tau 1_k}\right)^{n_k}n_k(\tau 2_k)^2+\left(\frac{t}{\tau 1_k}\right)^{n_k}n_k^{\,2}(\tau 2_k)^2+2t\left(\frac{t}{\tau 1_k}\right)^{n_k}n_k\tau 2_k\right]}{t^2\left[\left(\frac{t}{\tau 1_k}\right)^{n_k}+1\right]^3\eta_k(\tau 2_k)^2} \tag{3}$$

$$\text{Charge transferred: } \int i(t)dt=\int\sum_{k=1}^{m}\frac{I0_k}{\eta_k}e^{-\frac{t}{\tau 2_k}}\frac{\left(\frac{t}{\tau 1_k}\right)^{n_k}}{1+\left(\frac{t}{\tau 1_k}\right)^{n_k}}dt \tag{4}$$

$$\text{Action integral: } \int i^2(t)dt=\int\left[\sum_{k=1}^{m}\frac{I0_k}{\eta_k}e^{-\frac{t}{\tau 2_k}}\frac{\left(\frac{t}{\tau 1_k}\right)^{n_k}}{1+\left(\frac{t}{\tau 1_k}\right)^{n_k}}\right]^2dt \tag{5}$$

Negative Subsequent Stroke: We first examine the negative subsequent stroke because it is the simplest to represent. To synthesize accurately a typical negative subsequent stroke waveform, only two Heidler functions are necessary, i.e., m = 2 only, in the expressions above. The values for the four adjustable parameters are given in Table 3; and plots for the current, the first derivative of the current, and the second derivative are shown in Fig. 1, Fig. 2, and Fig. 3, respectively. Parameters exhibited by the plotted waveforms are given in Table 4. The Fourier transform of the negative subsequent stroke current is shown in Fig. 4.

Table 3. Calculated Values of Heidler Function Parameters for a Negative Subsequent Stroke Current

K	$I0_k\,(kA)$	n_k	$\tau 1_k\,(\mu s)$	$\tau 2_k\,(\mu s)$
1	7.5	55	1.1	15
2	5	2	1.2	500

Table 4. Measured Parameters of Waveform Synthesized Using Parameters from Table 3

$I_{peak}\,(kA)$	$\left(\frac{di}{dt}\right)_{\max}\,(kA/\mu s)$	$\tau_{10to90risetime}\,(\mu s)$	$\tau_{Peakto50decaytime}\,(\mu s)$
11.3	97	0.58	34.8

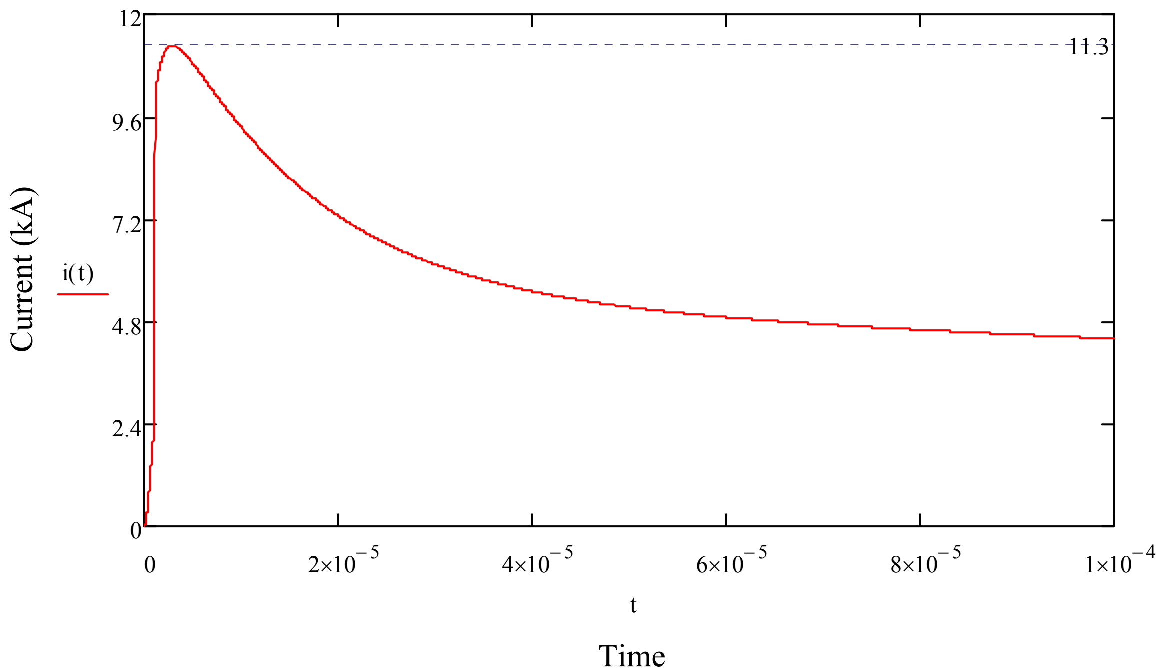

Fig 1. Negative Subsequent Stroke Current Waveform.

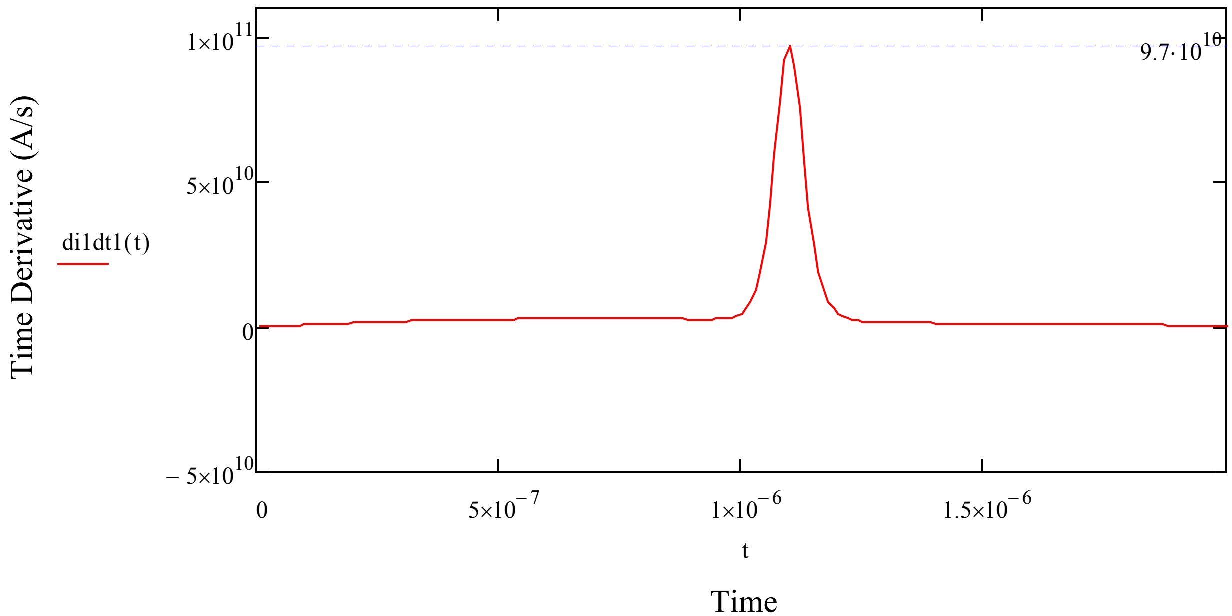

Fig 2. First Time Derivative of Negative Subsequent Stroke Current.

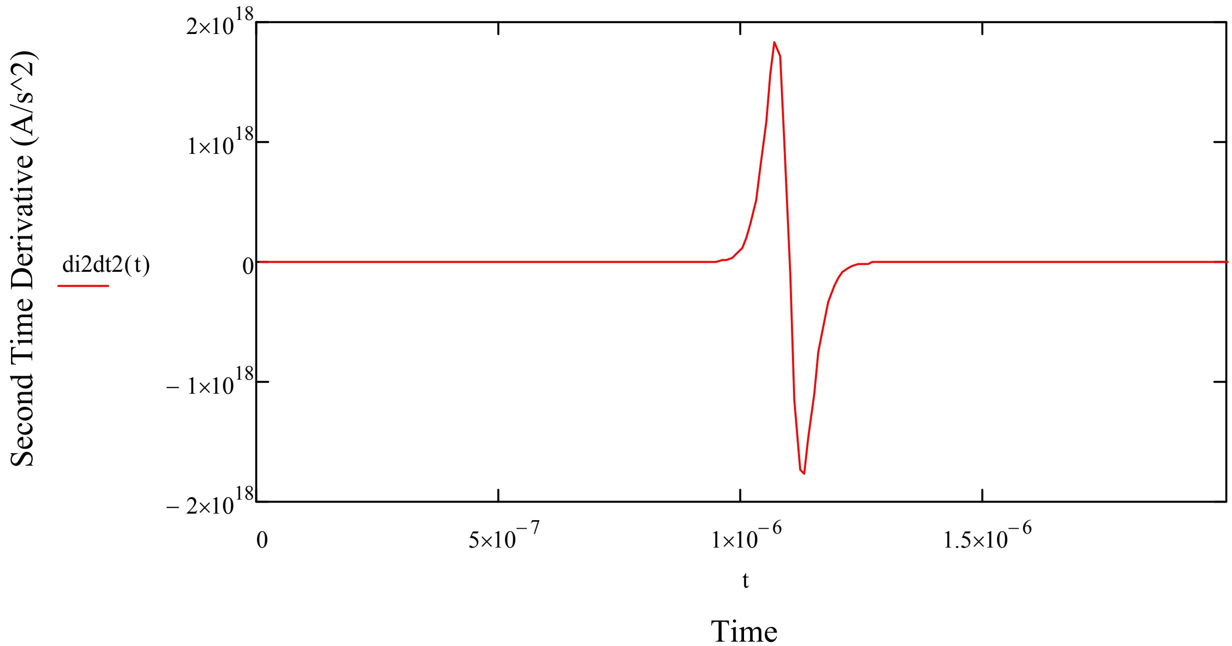

Fig 3. Second Time Derivative of Negative Subsequent Stroke Current.

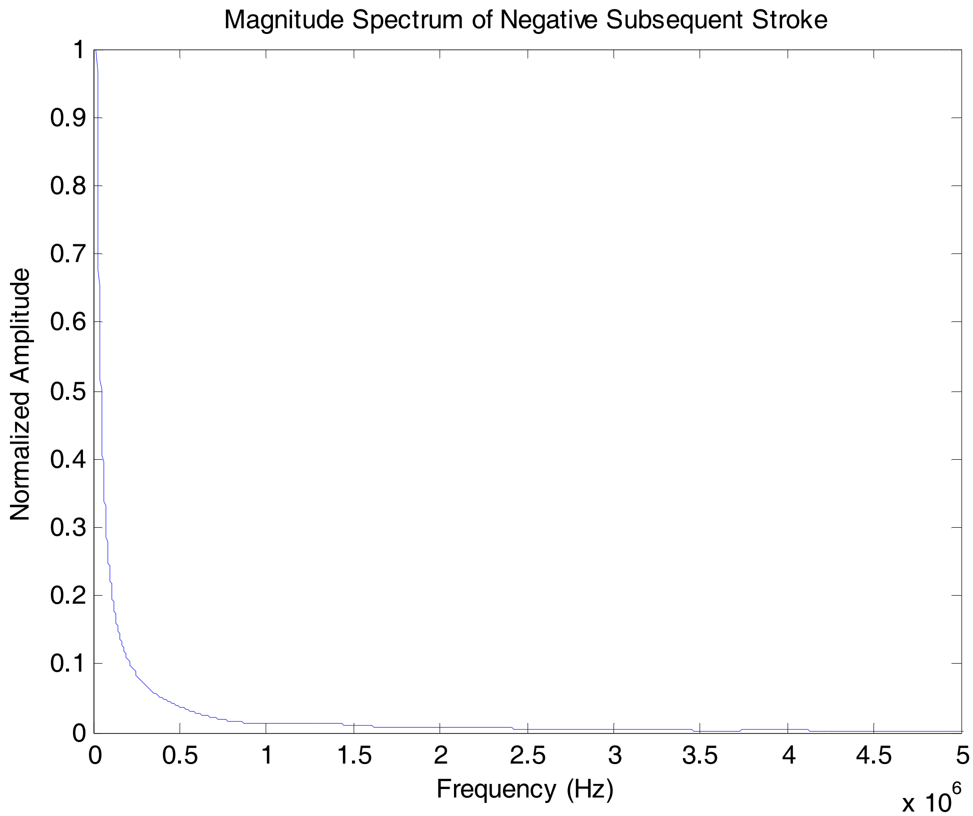

Fig 4. Fourier Transform of Negative Subsequent Stroke Current. Value at dc is unity.

Negative First Stroke: To represent a negative first stroke waveform, we sum 6 Heidler functions (m = 1 - 6). The parameters used for each Heidler function are shown in Table 5. Fig. 5 shows the current. Fig. 6 shows the first derivative of the current, and Fig. 7 shows the second derivative. The parameters measured from the plotted waveforms are shown in Table 6.

The negative first stroke current rise to peak value consists of a "slow front" of some microseconds followed by a "fast transition" of tenths of a microsecond to the peak value during which time the maximum current derivative occurs, as observed on towers in Switzerland (Berger et al. 1975), Brasil (DeConti and Visacro 2007), and as inferred from electric field measurements (e.g., Jerauld et al. 2007). For the first-stroke constants given, the negative first-stroke charge transfer is 5.2 C, and the action integral is $7.1*10^4$ A^2s.

The Fourier transform of the negative first stroke current is given in Fig. 8.

Negative Continuing current: One Heidler function is used to produce the waveform (Fig. 9) for the negative continuing current. The values for the parameters are summarized in Table 7. Quantities measured from the analytical waveform are found in Table 8. Fig. 10 and 11 show the first and the second time derivative of the continuing current waveform, respectively. The continuing current charge transfer is 20.6 C, and the action integral is $2.1*10^3$ A^2s. For the negative continuing current, if the decay-time constant, $\tau 2$, is reduced by half, the total charge transfer will also be reduced by half, and so will the peak to half-peak decay time.

Severe (1%) Parameters for a Negative Flash: Functional expressions are given above for negative first and subsequent strokes and for continuing current and constants are chosen to produce the median parameters found in Table 2. To simulate a reasonable approximation to a negative flash having all 1% parameters, simply multiply the first and subsequent stroke current amplitudes for the median case by a factor of 5 and the continuing current amplitude for the median case by a factor of 10.

Table 5. Calculated Values of Heidler Function Parameters for Negative First Stroke Current

K	$I0_k\,(kA)$	n_k	$\tau 1_k\,(\mu s)$	$\tau 2_k\,(\mu s)$
1	3	2	4	20
2	3	3	4	20
3	3	9	4	20
4	3	11	4	20
5	20	85	4.5	23
6	15	2	20	240

Table 6. Measured Parameters of Negative First Stroke Waveform Synthesized Using Parameters from Table 5

$I_{peak}\,(kA)$	$\left(\frac{di}{dt}\right)_{\max}\,(kA/\mu s)$	$\tau_{peak}\,(\mu s)$	$\tau_{Peakto50decaytime}\,(\mu s)$
32.5	100	6	76

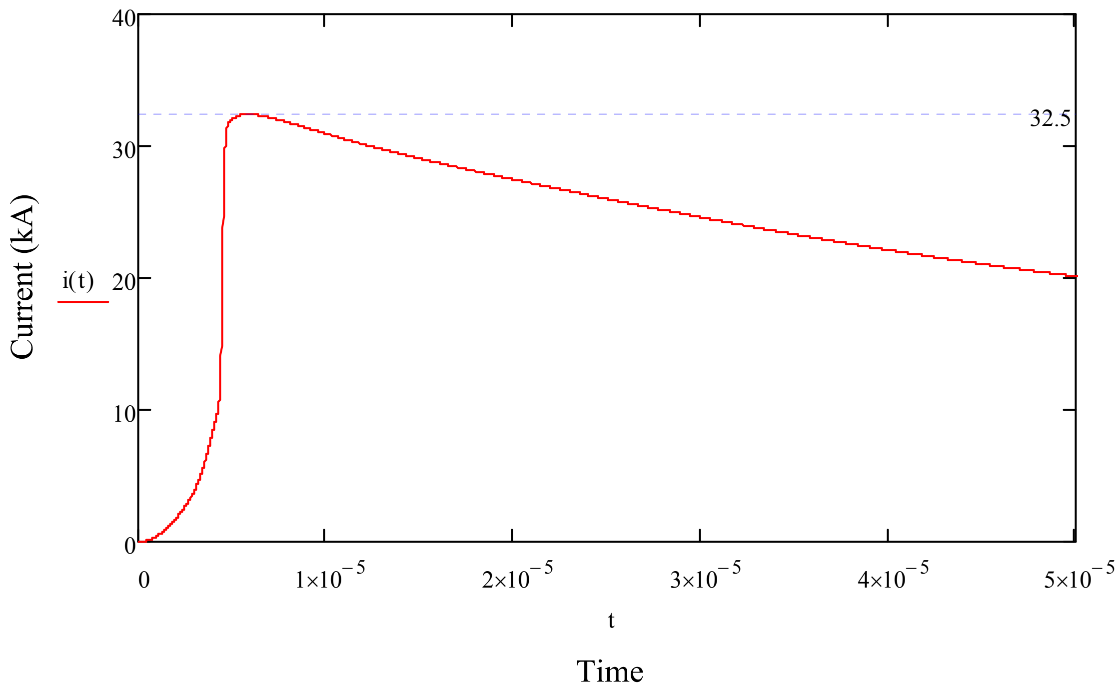

Fig 5. Negative First Stroke Current Waveform.

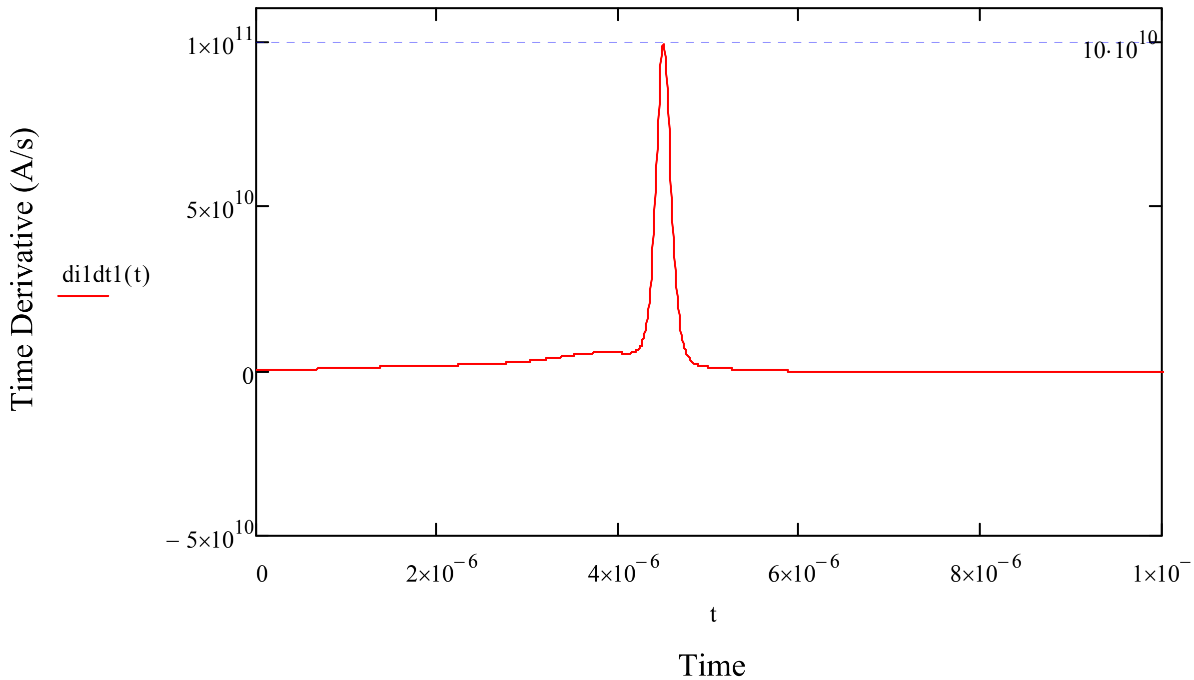

Fig 6. First Time Derivative of Negative First Stroke Current Waveform.

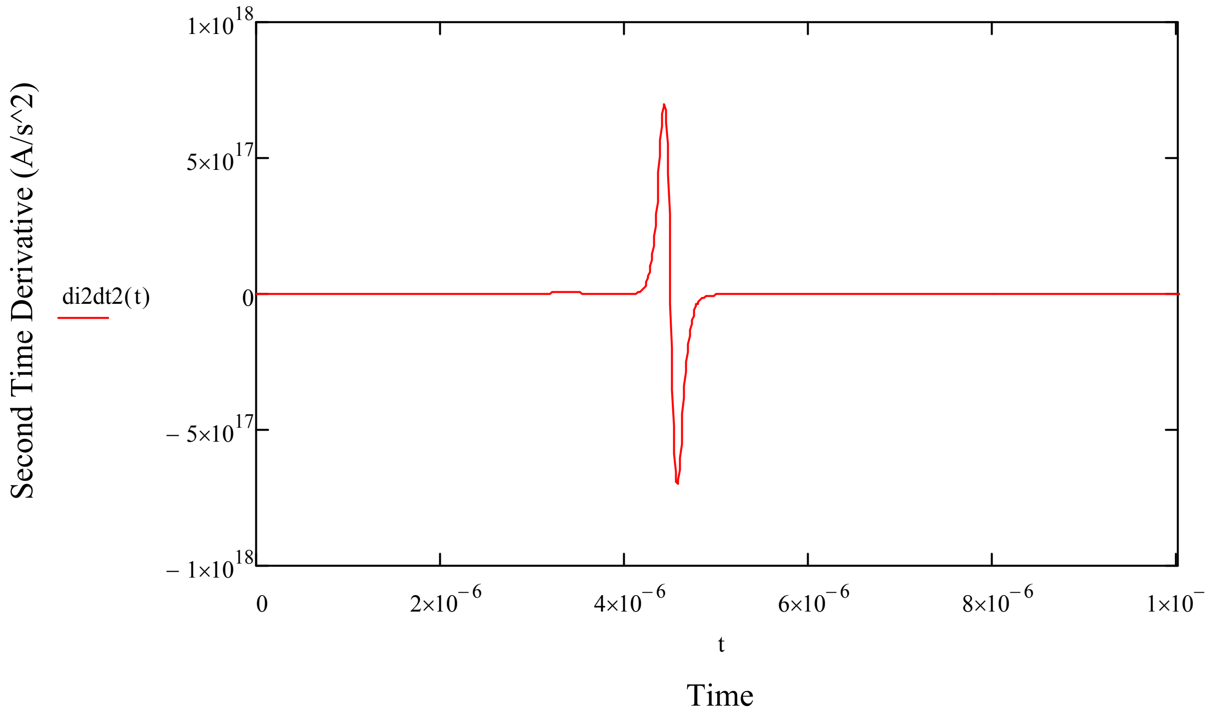

Fig 7. Second Time Derivative of Negative First Stroke Current Waveform.

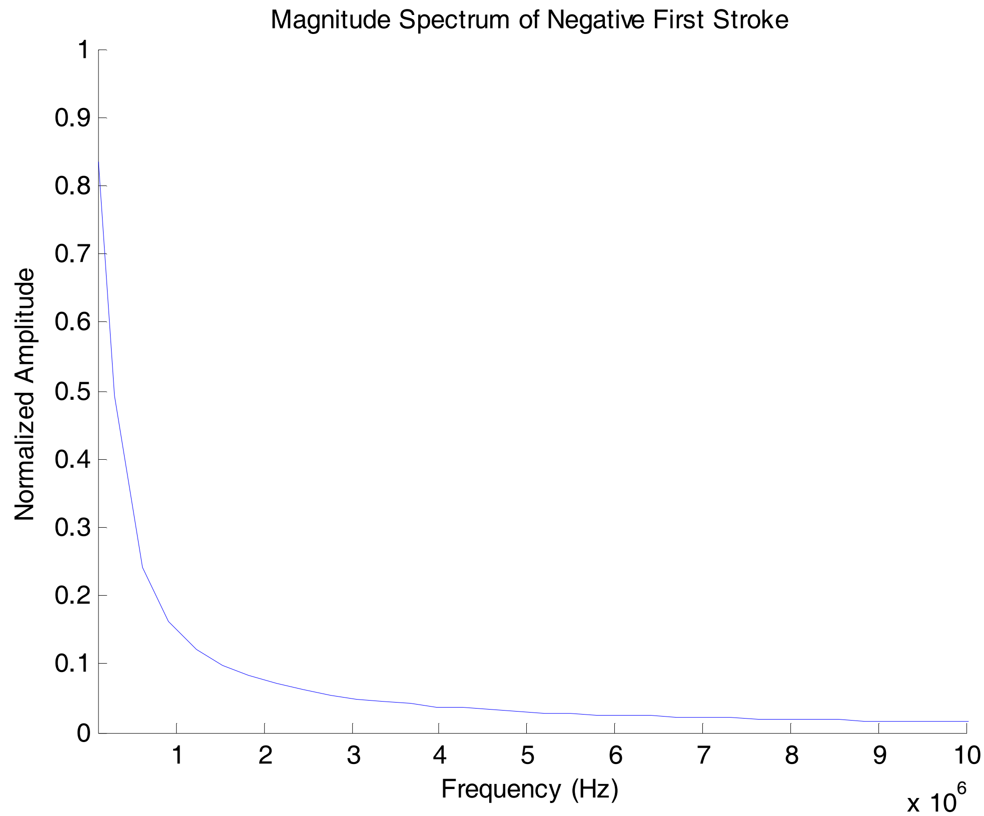

Fig 8. Fourier Transform of Negative First Stroke Current Waveform. The dc value is unity.

Table 7. Calculated Values of Heidler Function Parameters for Negative Continuing Current

$I0(A)$	n	$\tau 1(ms)$	$\tau 2(ms)$
200	9	4	100

Table 8. Measured Parameters of Negative Continuing Waveform Synthesized Using Parameters from Table 7

$I_{peak}(A)$	$\left(\frac{di}{dt}\right)_{\max}(A/\mu s)$	*Total Charge(C)*	$\tau_{Peakto50decaytime}(ms)$
199	0.119	20.6	70

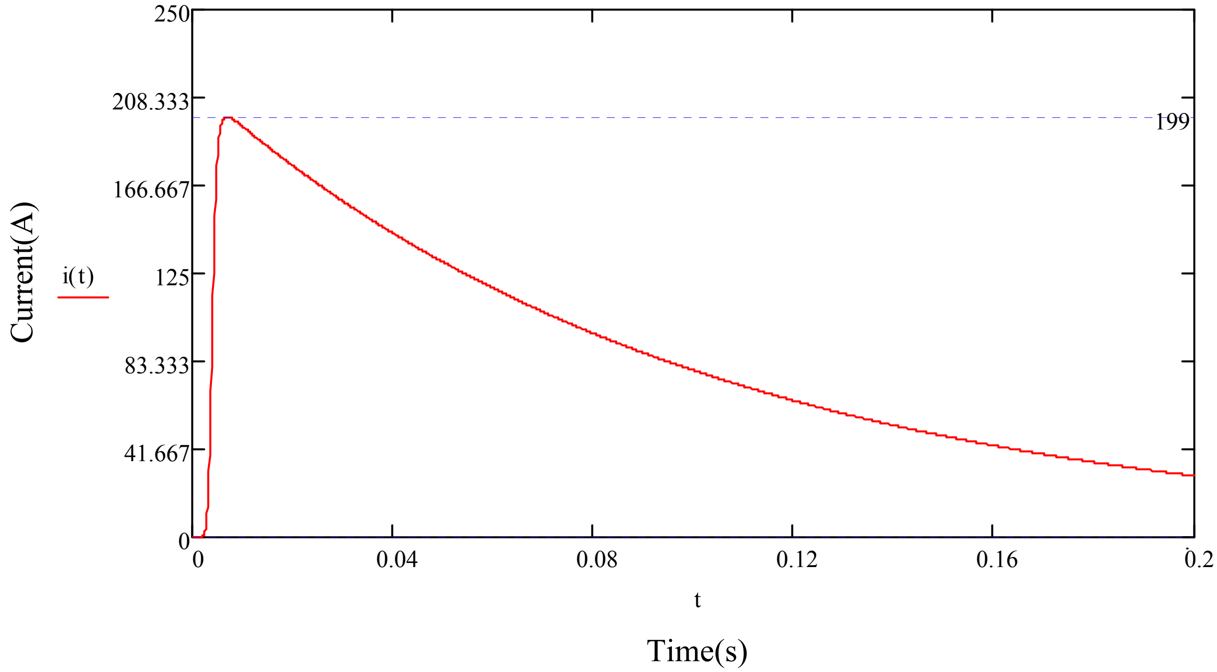

Fig 9. Negative Continuing Current Waveform.

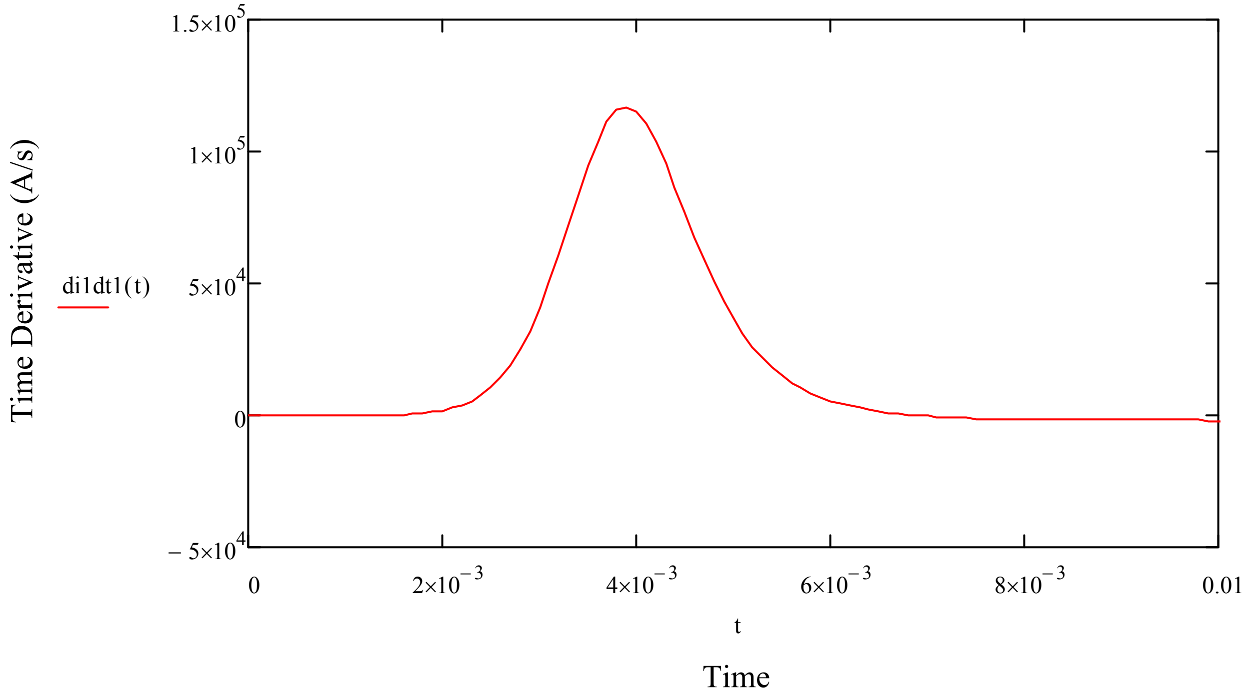

Fig 10. First Time Derivative of Negative Continuing Current Waveform.

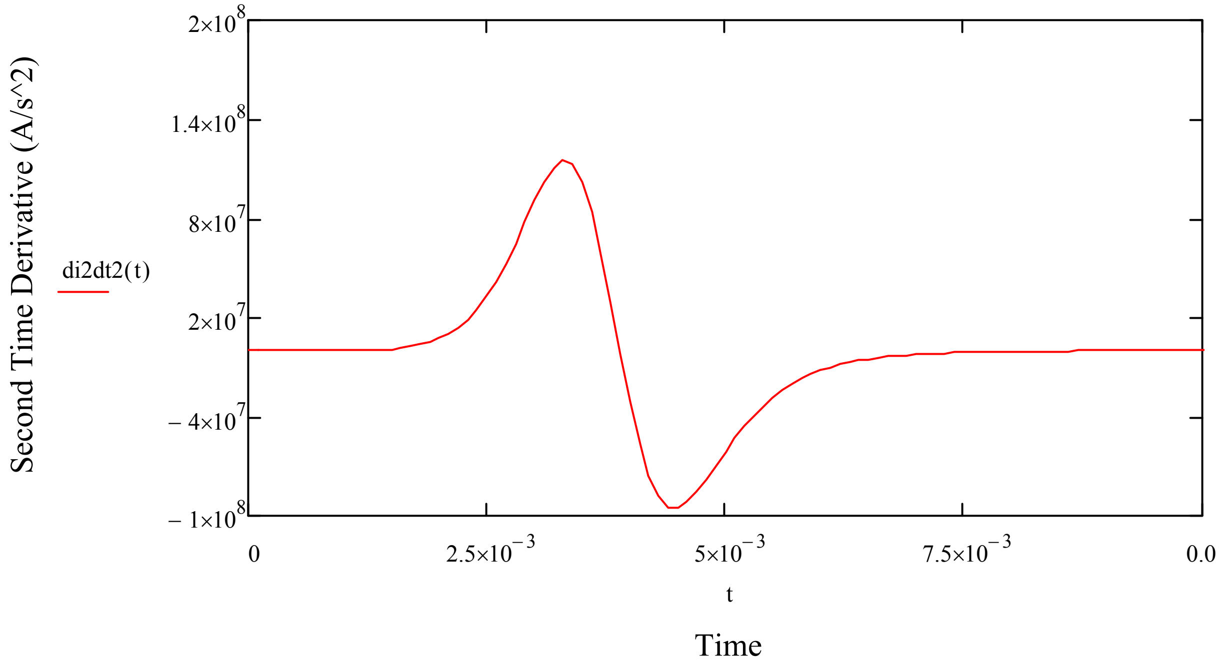

Fig 11. Second Time Derivative of Negative Continuing Current Waveform.

<u>Positive First Stroke:</u> To represent a positive first stroke waveform, we sum 4 Heidler functions (m = 1 - 4). The parameters used for each Heidler function are shown in Table 9. Fig. 12 shows the current. Fig. 13 shows the first derivative of the current, and Fig. 14 shows the second derivative. The parameters measured from the plotted waveforms are shown in Table 10. The positive first stroke charge transfer is 1.7 C and the action integral is 3.2*10^4 A^2s.

<u>Positive Continuing current:</u> One Heidler function is used to produce the waveform (Fig. 16) for the positive continuing current. The values for the parameters are summarized in Table 11. Quantities measured from the analytical waveform are found in Table 12. Fig. 17 and 18 show the first and the second time derivative of the continuing current waveform, respectively. The action integral is 4.07*10^4 A^2s.

<u>Severe (1%) Parameters for a Positive Flash</u>: To simulate the peak currents of a positive flash having close to 1% parameters, simply multiply the median first positive stroke amplitude and the median continuing current amplitude by a factor of 10. The resultant flash action integral is 7.3*10^6, 4.07*10^6 A^2s for the continuing current, and 3.2*10^6 A^2s for the positive first stroke. To produce almost exactly the 1% flash action integral in Table 2, the median and stroke continuing current amplitudes should be multiplied by a factor of 30. In this case, the peak currents are larger than the values given in Table 2. Alternately, the first positive stroke amplitude could be multiplied by a factor of 10 and the continuing current amplitude by a factor of 45.

Table 9. Calculated Values of Heidler Function Parameters for a Positive First Stroke Current

K	$I0_k (kA)$	n_k	$\tau 1_k (\mu s)$	$\tau 2_k (\mu s)$
1	20	116	6	50
2	5	3	9	20
3	6	2.5	8	30
4	7	4	6	30

Table 10. Measured Parameters of Positive First Stroke Waveform Synthesized Using Parameters from Table 9.

$I_{peak} (kA)$	$\left(\frac{di}{dt}\right)_{\max} (kA/\mu s)$	$\tau_{Peak} (\mu s)$	$\tau_{10to90risetime} (\mu s)$	$\tau_{Peakto50decaytime} (\mu s)$
35	100	11	3	30

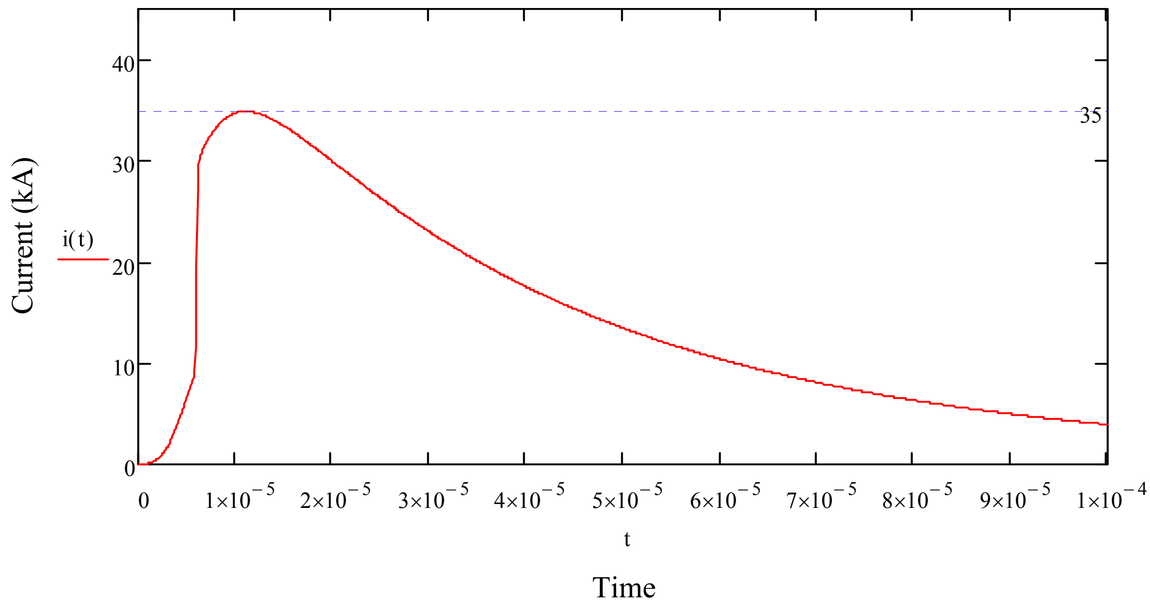

Fig 12. Positive First Stroke Current Waveform.

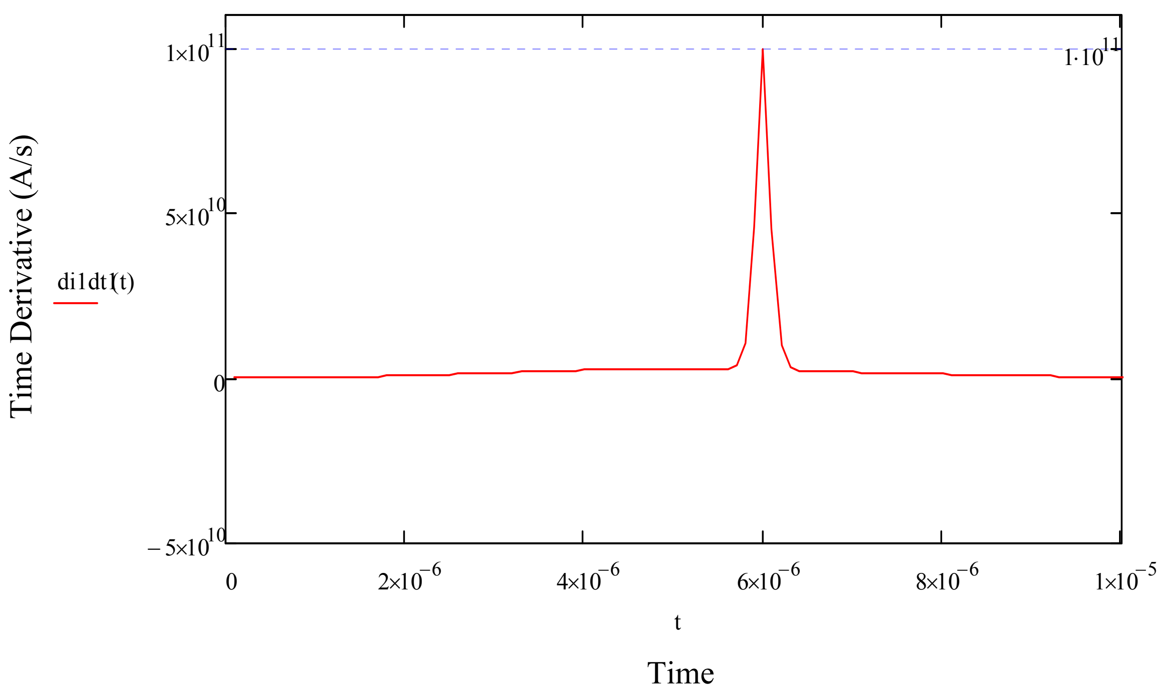

Fig 13. First Time Derivative of Positive First Stroke Current Waveform.

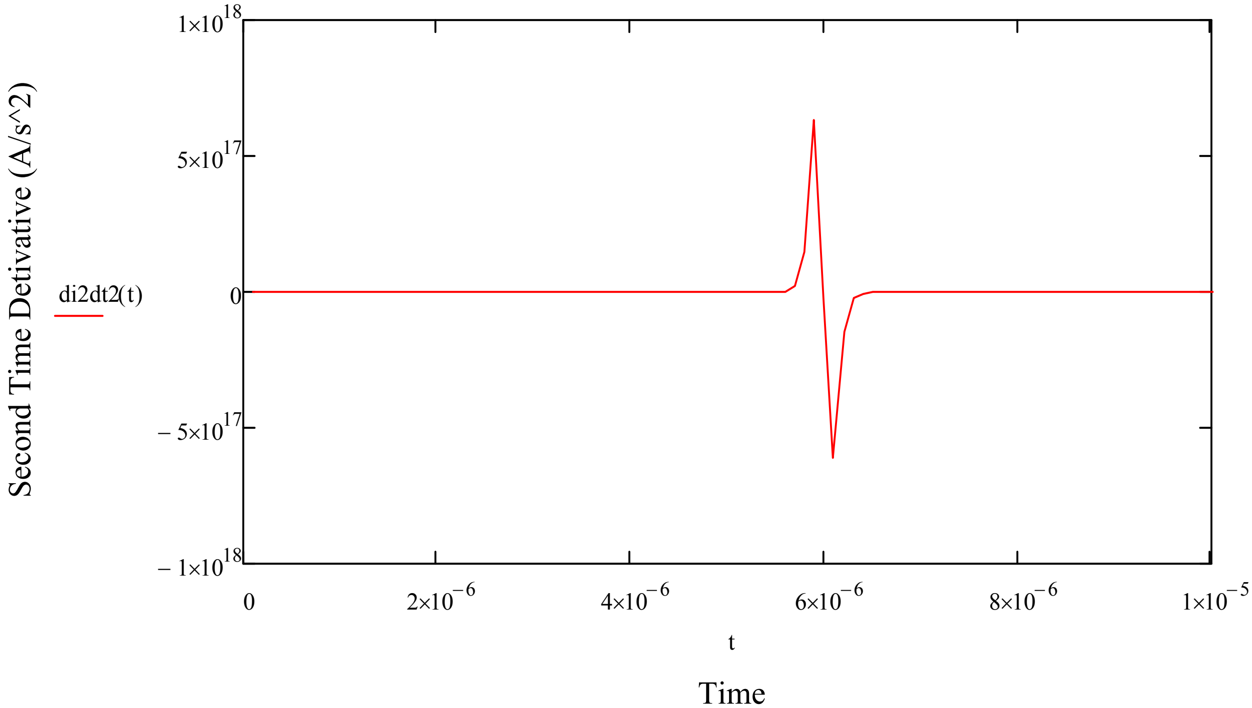

Fig 14. Second Time Derivative of Positive First Stroke Current Waveform.

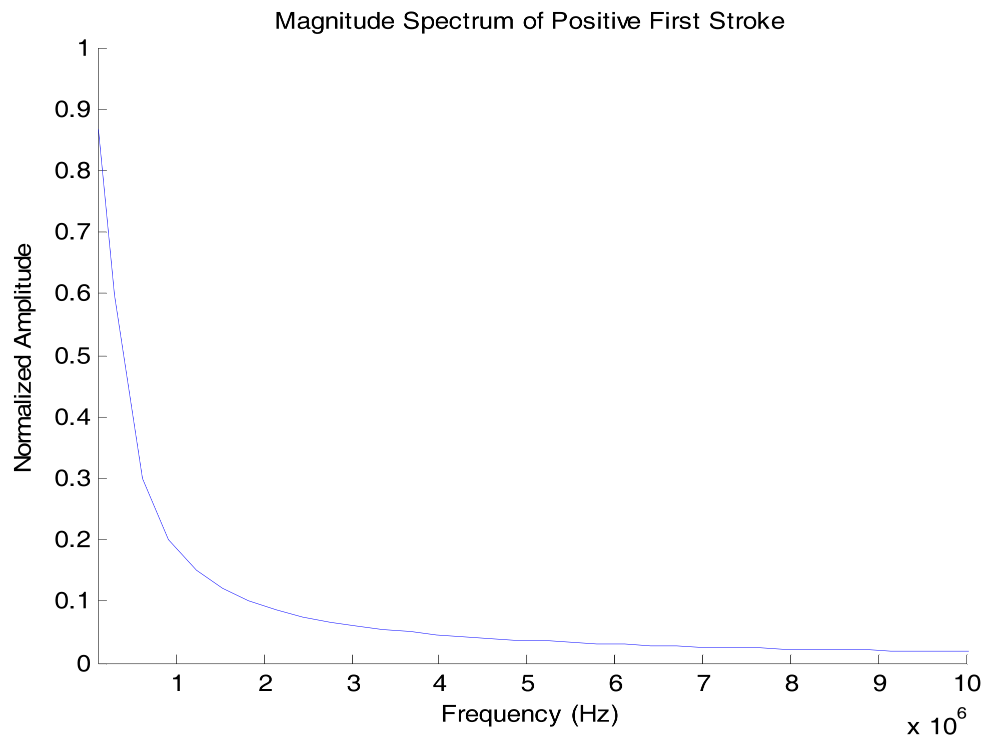

Fig 15. Fourier Transform of Positive First Stroke Current Waveform. The dc value is unity.

Table 11. Calculated Values of Heidler Function Parameters for Positive Continuing Current

$I0(kA)$	n	$\tau 1(ms)$	$\tau 2(ms)$
1	9	3	77

Table 12. Measured Parameters of Positive Continuing Waveform Synthesized Using Parameters from Table 11

$I_{peak}\,(kA)$	$\left(\frac{di}{dt}\right)_{\max}\,(A/\mu s)$	*Total Charge(C)*	$\tau_{Peakto\,50\,decaytime}\,(ms)$
1	0.78	80	55

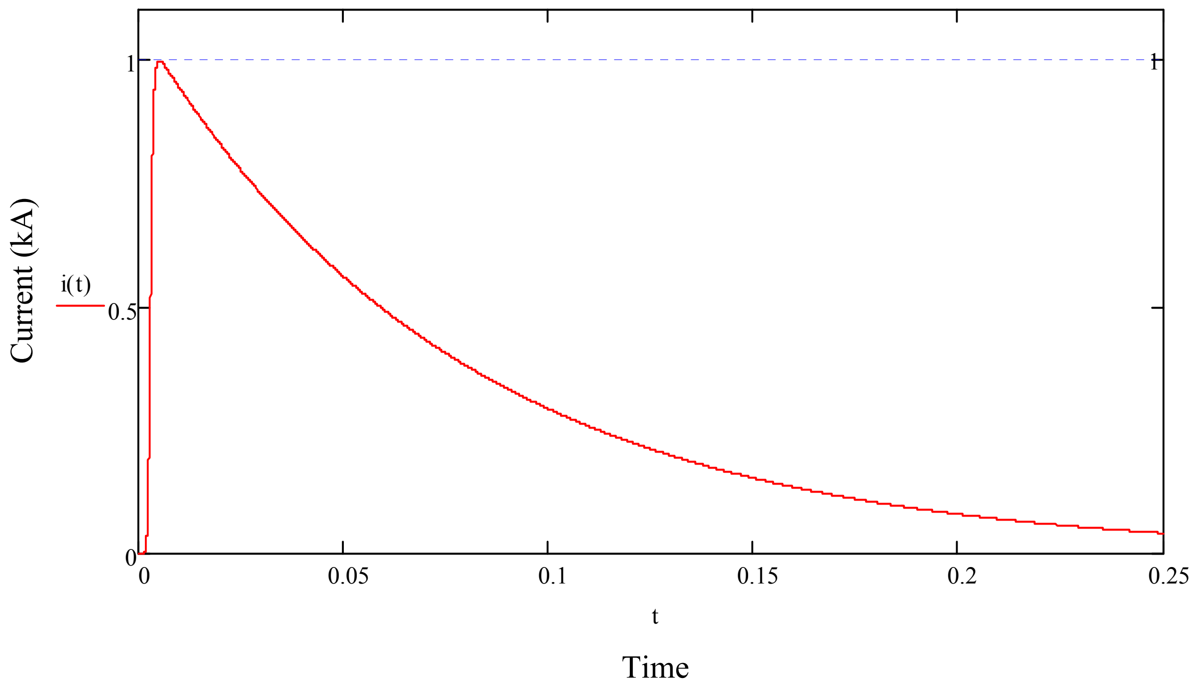

Fig 16. Positive Continuing Current Waveform.

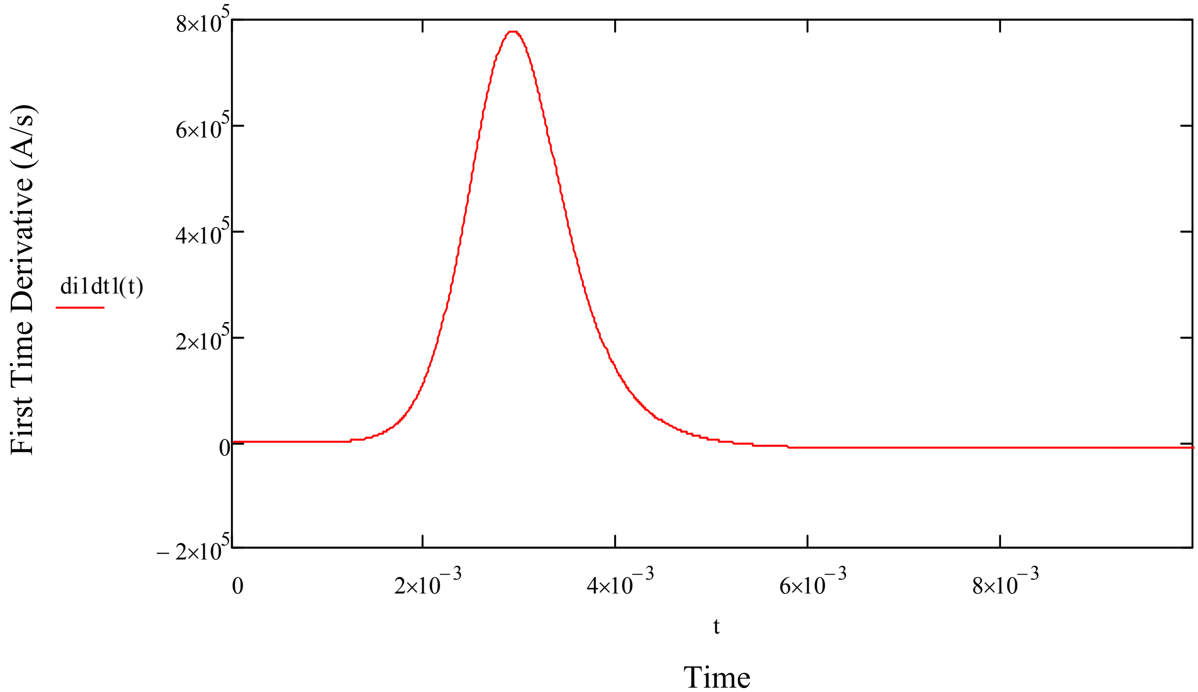

Fig 17. First Time Derivative of Positive Continuing Current Waveform.

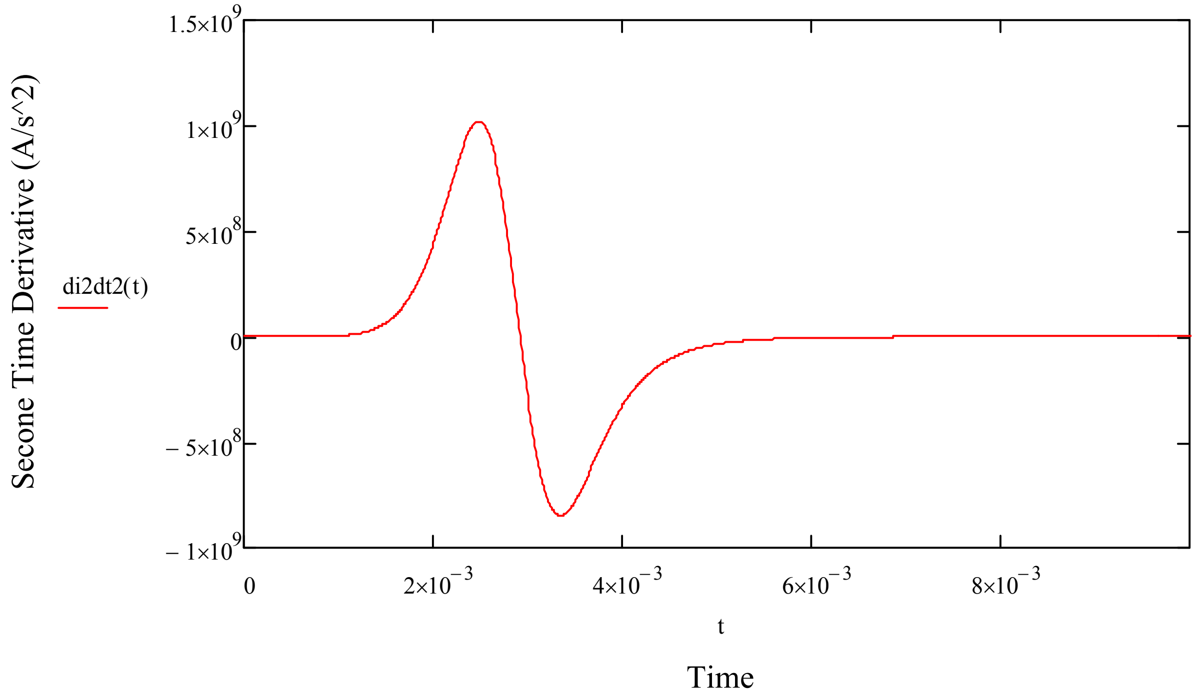

Fig 18. Second Time Derivative of Positive Continuing Current Waveform.

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Appendix 1: Return Stroke Current

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Appendix 2: Continuing Current

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