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Statistics on Radiation Field Waveforms Associated with Multiple Intracloud Lightning Discharges

Bok-Hee Lee, Dong-Moon Lee, Chang-Hwan Ahn and Young-Bong Kim

Abstract - This paper presents the detailed statistics on radiation field signatures associated with multiple-intracloud lightning discharges. A transient signal recording system was used to measure the electric and magnetic fields produced by lightning flashes. The measurements were made in the summers of 1995 through 1999, and the location of the observation station was in Inchon on the coast of the Yellow Sea in Korea(37° 25'N, 126° 39'E). Most of lightning flashes typically contains between two and five strokes. The individual intracloud stroke radiation fields were the bipolar pulses with a large overshoot into the opposite polarity after the peak. The narrow stepwise pulses were usually superimposed on the bipolar pulse. On the average, the ratio of the peak of the second stroke to the first stroke peak was 75.1±42.8% for the positive polarity and 71.0±40.1% for the negative, and a fraction of the subsequent stroke peaks were higher than the first stroke peak. The greater the number of the subsequent stroke order, less time separations between strokes were produced. The mean of the depth of the dip was 81.2±27.9% for the positive polarity and 75.9±24.4% for the negative. The depth of the dip increased for the positive bipolar pulses and decreased for the negative as the number of the stroke order increased.

Key Word - Lightning property, Radiation field, Intracloud lightning, Multiple-intracloud flash, Field parameter, Bipolar pulse, Stepped leader, Stroke occurrence

1. Introduction

A source of severe electromagnetic interferences emits from lightning discharges. The usual lightning discharges release high energy of the order of megajoule. Most of sensitive electronic systems result in their erratic operation or even damage with the energy level of the order of millijoule. An increasing use of electric devices is in recent years employed in wide fields of industry and business of which info-telecommunication, control and protection system are essential and important. The transient overvoltage from intracloud lightning discharges can cause failure, permanent degradation, or temporary maloperation of electronic devices and systems. Therefore, recent concerns about damage caused by the induced lightning overvoltage have focused on semiconductors. There is a need for careful, effective protection of electronic circuits from lightning electromagnetic field pulses. In order to develop techniques for protection against lightning transient overvoltage, it is of great importance to investigate the characteristics of radiation fields produced by lightning discharge processes.

Much effort has been devoted to finding the statisticson the parameters of radiation field wave shapes associated with lightning flashes. Cloud-to-ground lightning return strokes have been studied extensively because of its practical interest world widely. In contrast to cloud-to-ground lightning return strokes, rather little is known about the characteristics of intracloud lightning discharges. Only a few data of radiation fields produced by intracloud lightning discharges were reported.[1-5] The radiation fields associated with intracloud lightning discharges were entirely different from those with cloud-to-ground lightning return strokes. The radiation fields produced by the primary strokes showed the bipolar pattern and had always one or more pulses superimposed on the initial half-cycle of the bipolar pulses which overshoot into the opposite polarity after the peak. The overall structure and features of the radiation field wave shapes from intracloud lightning discharges are very similar to those observed in Florida by Krider, Weidman and LeVine[6], in Sweden by Cooray and Lundquist[7], and in Japan by Hojo et al.[8]. Weidman and Krider have suggested that the pronounced bipolar pulses are caused by a slow current surge and that the narrow pulses superimposed on the initial half-cycle of the bipolar components are caused by the extension of the channel in a stepped process.[9] Recently characteristics for electric field pulses in close lightning cloud flashes and microsecond-scale electric field pulses in cloud lightning discharges have reported.[10-11]

Thus the goal of the study presented in this paper is to analyze the overall characteristics of intracloud stroke radiation fields. Here we report for the first time the detailed statistics on the parameters of the radiation fields

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produced by multiple-intracloud lightning discharges. The value of voltage, current, or power that is necessary to cause permanent damage to semiconductor devices is a function of the waveform of induced lightning overvoltage and is particularly sensitive to the duration of the transient overvoltages. The field parameters such as the time separation between subsequent strokes, the ratio of the peak of the subsequent strokes to the first stroke peak, and the depth of the dip in the opposite polarity of the bipolar pulse were examined for the positive and negative radiation fields. Also, the occurrence frequency and the time separation between the stepwise narrow pulses superimposed on the initial half-cycle of the bipolar pulse were analyzed. All data examined here were measured during the summers since 1995 at the high voltage laboratory of Inha University in Inchon. The results will provide the valuable information about a better understanding of intracloud lightning discharge physics and an effective protection of electronic circuits.

2. The measurement system

The measurement system consists of a hemisphere electric field sensor with amplifier and buffer, the crossed-loop magnetic field sensor combined with an active integrator and the transient data recorder, and its schematic diagram was shown in Fig. 1. The authors have already developed the electric and magnetic field measurement system having a high sensitivity and wide bandwidth and the details have reported in the literature.[12,13] Since we have no the devices for measuring the distance between the intracloud lightning discharge point and the observation station, the magnetic field was simultaneously observed to verify that whether the electric field signature associated with intracloud lightning discharges is the same shape as the magnetic field or not.

The electric field measurement system with a 3 dB bandwidth from 200 Hz to 1.6 MHz was employed. The frequency bandwidth of the magnetic field measurement system ranges from 270 Hz to 2.3 MHz. The electric and magnetic field signatures were simultaneously recorded by a transient signal analyzer with the vertical resolution of 12 bit and the recording length of 5 kilowords per event, and they were transferred to a personal computer. The transient signal analyzer is triggered by the field signature to be measured, and it is operated in the pretrigger mode so that the radiation field signatures before and after the trigger pulse can be displayed. The measurement system was entirely suitable to observe the transient radiation field signatures of interest.

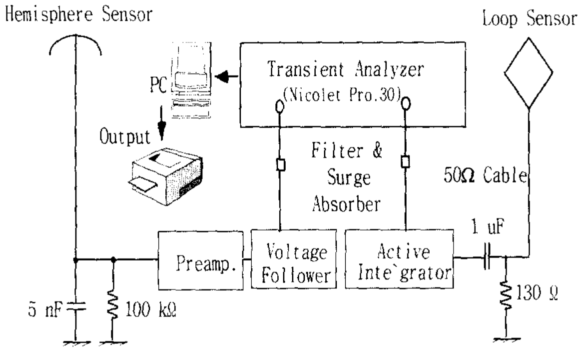


Fig. 1 Schematic diagram of the experimental system for measuring the electric and magnetic fields.

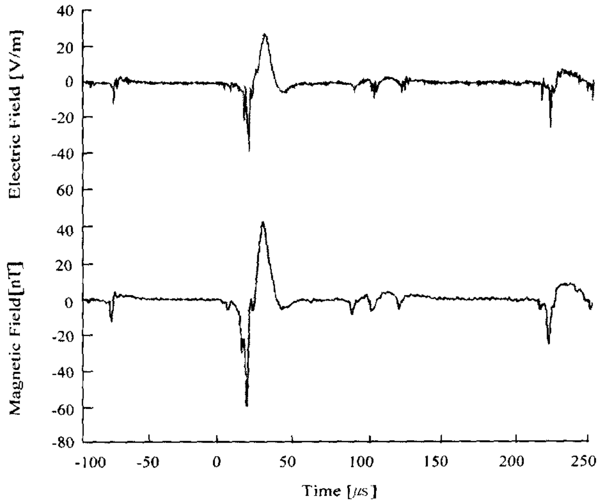
3. Results and Discussion

3.1 The features of the radiation fields

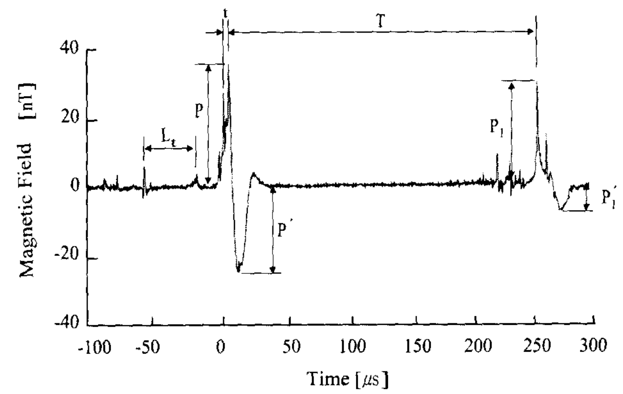
An intracloud lightning discharge, which is a lightning discharge of the most frequent occurrence, takes place between the oppositely-charged centers within the same cloud. The wave shapes of the electric and magnetic fields produced by lightning discharges in the general field expressions are varied with the distance from the lightning stroke location to the observation point[14,15]. The radiation fields are substantially produced by intracloud lightning discharges from the distance of more than 20 km[9]. In the present paper, we will discuss in detail the features and relevant parameters of multiple-intracloud lightning stroke radiation fields.

A positive electric field at the ground is produced by the deposition of negative charge overhead according to the atmosphere electricity sign convention. Generally the radiation fields produced by cloud flashes are referred to as the positive cloud pulses or negative cloud pulses according to their initial polarity[7].

Figure 2 displays the fine structure of the electric and magnetic fields and the revelant parameters for the radiation fields produced by multiple-intracloud lightning discharges. Parameters of lightning electromagnetic field pulses are important for aspects of lightning damage and upset. For example, the rate of change of electric and magnetic field pulses is a critical factor for interference voltage considerations and the duration of the pulses is significant for energy ratings of suppressors. The structure of the radiation fields due to intracloud lightning discharges might be produced by abrupt variations in either the channel current, channel geometry, or the strokes associated with the branch components. The electric field waveform of the bipolar pulses appears to be relatively smooth and the overall width of the bipolar pulses is in the range 20-30 μs. J. C. Willett, et al. have proposed that the biolar pulses are not associated with K-changes in intracloud lightning discharges or other identified lightning processes[16].



(a) Wave shapes of the electric and magnetic fields



(b) Definition of the field parameters

Fig. 2 Typical wave shapes of the electric and magnetic fields and the definition of the relevant field parameters in multiple intracloud lightning discharges

Unfortunately, the origin of the bipolar pulses of radiation fields, as illustrated in Fig. 2, is still not clearly understood. The stepped pulses with a width of a few microseconds were appeared just before the main stroke, and it is believed that the intermittent pulses are probably produced by a leader process. Intracloud lightning discharges begin with the preceding leader streamers which develop with a stepwise propagation toward the oppositely charged center. The leader streamer reaches at a localized concentration of the opposite polarity charge and then the primary stroke launches. The time separations between the stepped leader pulses are somewhat irregular and the successive leader pulses have relatively small amplitude in comparison with the peak of the primary stroke fields. The preceding irregular pulses are to be associated with the simultaneous propagation process toward each other of the downward negative stepped leader and the upward positive connecting streamer[17].

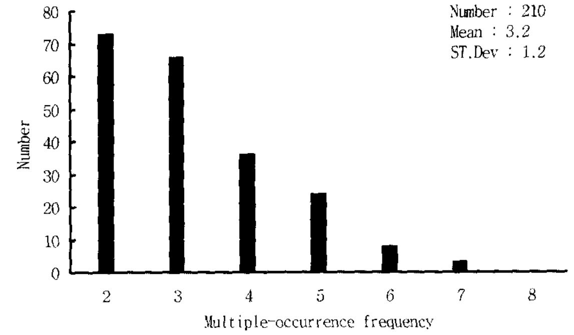
The structure and temporal processes of the radiation fields produced by subsequent strokes are substantially identical to the first stroke fields, as illustrated in Fig.2. It is inferred that the multiple-radiation fields are associated with the lightning channels having multiple-terminations on the surface of cloud or the lightning channels having single attachments due to multiple-charged cell. Multiple-strokes in a flash are associated not with an individual multiple-developed leader but rather than with the deflection of a subsequent leader from the previously created channel[18].

3.2 The parameters of the radiation fields

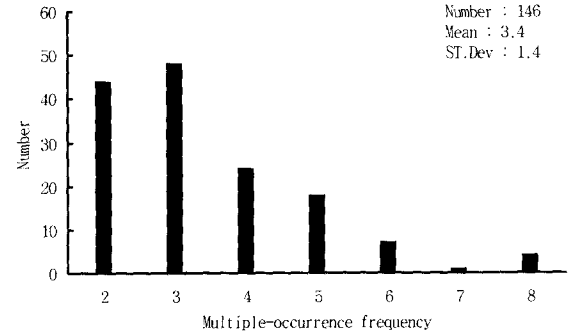
The radiation fields produced by intracloud lightning discharges were highly irregular in wave shape. The statistical analysis is a very suitable means because of the erratic nature of lightning flashes. Thus our statistics are focused on the occurrence number, time differences and amplitude ratios for the electromagnetic fields produced by multiple in-cloud lightning discharges.

3.2.1 The occurrence frequency

Figure 3 illustrates histograms of the occurrence frequency of intracloud lightning discharges as a function



(a) Positive



(b) Negative

Fig. 3 Histograms of the multiple-occurrence frequency of intracloud lightning discharges plotted as a function of stroke order.

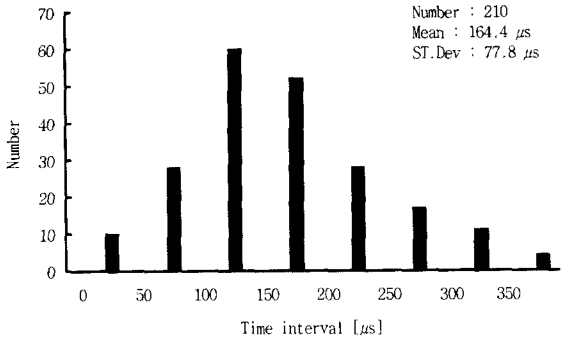
of stroke order. Only radiation fields with a fine structure were analyzed in this statistics and the number of the data is not the total occurrence frequency of intracloud lightning discharges during the observation period. The maximum 8 subsequent strokes were measured because of the limitations of the data recording length of the measuring system used in this work. Most of the multiple-occurrence frequency were distributed within the range of less than 5. The multiple-occurrence frequency of the radiation fields was a mean of 3.2±1.2 for the positive polarity and 3.4±1.4 for the negative. The mean of the multiple-occurrence frequency for the positive polarity was roughly same as that for the negative. As a consequence, we can see that a lightning flash typically contains between three and five stroke sequences. The major effects of lightning electromagnetic pulses, which were computer data and software corruption or disturbance, might also be made worse by the multiple pulse aspect of lightning. The combination of the first stroke plus some subsequent strokes has a capability of causing considerable problems in the correct operation of a computer.

3.2.2 The subsequent stroke sequences

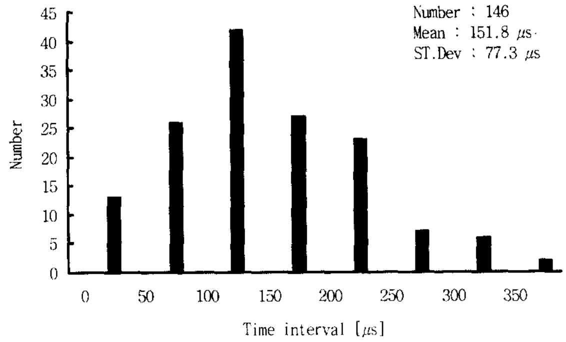
A multitude of radiation fields that were produced by intracloud lightning discharges have been observed as a multiple pulse train. The successive leader-stroke sequence can be developed in the same channel initiated by multiple-channel terminations due to different branches of the same stepped leader[19,20]. The mechanism of multiple-intracloud strokes in a flash was not completely understood. Figure 4 illustrates histograms of the time separation between the first and the second strokes. The mean of the time separations between the first and the second strokes was 164.4±77.9 μs for the positive fields and 151.9±77.3 μs for the negative, respectively. The mean of the time separations for the positive fields is in reasonable agreement with the data observed in Florida[9].

Trends of the time separations between subsequent stroke fields in a sequence were summarized as a function of stroke orders in Fig. 5, where the nth separation represents the time interval between the nth and (n+1)th strokes. The physical implication of the time separation between subsequent strokes is not clear yet. Thomson et al.[21] have explained through the observations of more than one channel below cloud base that a subsequent leader begins at the origin of the previous leader, follows the upper part of the old channel, branches into a new path before reaching cloud base.

Because the original and subsequent leaders in this case have a common origin, they have suggested that the possible mechanism governing the time separation between subsequent strokes, and hence the distribution of time separations between the subsequent strokes, is independent of whether a subsequent leader follows the



(a) Positive



(b) Negative

Fig. 4 Histograms of the time separations between the first and the second strokes.

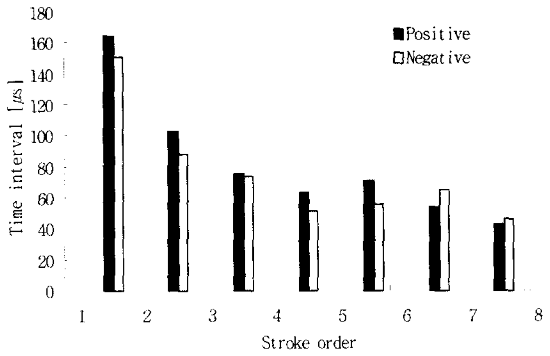
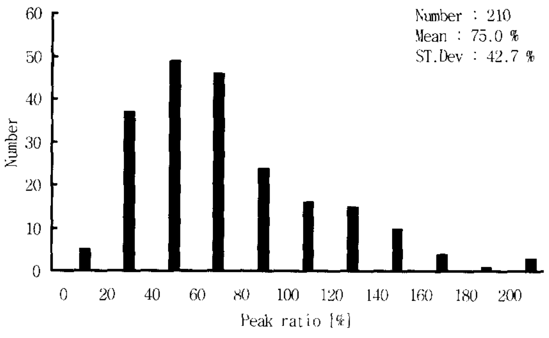
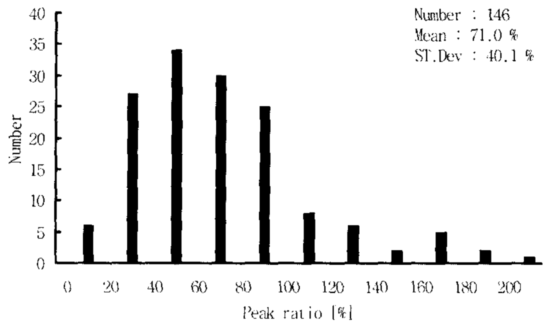


Fig. 5 Trends of the time separations between subsequent strokes as a function of stroke order. original channel or forms a separately new channel below cloud base.

The means of the time separations between the positive subsequent stroke pulses were somewhat larger than those for the negative. The mean of the time separation between the first and the second strokes is remarkedly large and the time separations between the subsequent stroke pulses gradually decreases as the stroke order increases. It was supposed that the time separations between subsequent stroke pulses are by degree shortened due to the channel formed by previous strokes. Namasivayam et al.[22] havereported that the mean of the time separations between



(a) Positive



(b) Negative

Fig. 6 Histograms of the ratio of the second stroke peak to the first stroke peak.

subsequent stroke pulses is 70.5 μs with a standard deviation of 66.4 μs. Also the present data were significantly longer than the mean of 52 μs in the radiation field changes of Japanese winter lightning reported by Ushio et al.[23]. From these results, it seems that the structure of radiation fields produced by intracloud lightning discharges depends on the geographical locations, the season and the meteorological conditions.

Distributions of the ratio of the second stroke field peak to the first stroke field peak (P2/P1) in the radiation fields associated with multiple-intracloud lightning discharges were shown in Fig. 6. Most of the ratio of the second stroke field peak to the first stroke field peak were distributed over the range 30 to 120%. The mean of the ratio of the second stroke peak to the first stroke peak was 75.1±42.8% for the positive and 71.0±40.1% for the negative bipolar pulses. Also the cases that the ratio of the subsequent stroke peak to the first stroke peak was more than 100% were about 30%. Lower-order subsequent strokes produced a greater initial peak than did higher-order strokes. The means of the amplitudes of the subsequent stroke peaks as a fraction of the first stroke peak in the bipolar radiation fields produced by multiple-intracloud lightning discharges were compiled as a function of stroke orders in Fig. 7. The peak ratio for the positive stroke fields was nearly unchangeable irrespective of stroke orders. On the other hand, the peak ratio for the negative stroke fields showed a little decrease before the third strokes and a great increase after the 4th strokes.

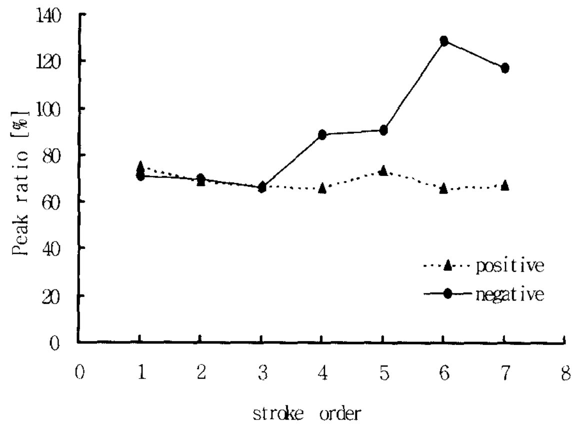
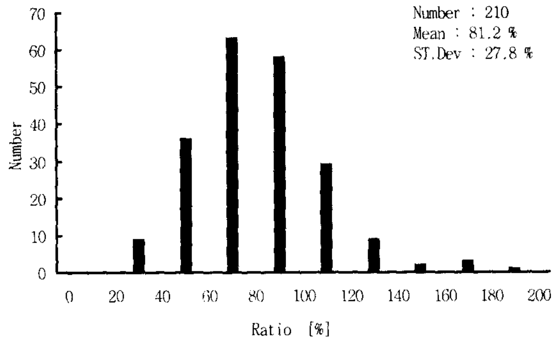


Fig. 7 Changes in the amplitude of the subsequent stroke field peak as a fraction of the first stroke field peak.

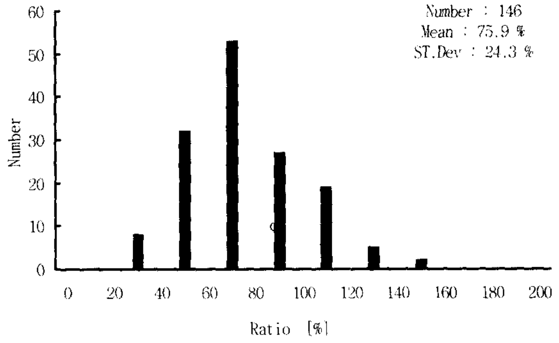
3.2.3 The depth of the dip

As described previously, the radiation fields produced by intracloud lightning discharges have usually had the bipolar pulses peak amplitudes comparable to those of cloud-to-ground lightning return stroke fields. The bipolar pulses of the radiation fields were originated from the primary stroke during the intracloud lightning discharge processes. In other words, the bipolar pulses are probably produced by the superposition of both the fast extension of the main channel and the current flowing through the channel created during the stepwise propagation processes, and they are the source of strong radio frequency radiations.

The depth of the dip (Pn/Pn') represents the ratio of the opposite direction peak relative to the first stroke peak in multiple-intracloud stroke fields. Figure 8 illustrates the histograms of the depth of the dip of the first stroke radiation fields. The mean of the depth of the dip was 81.2±27.9% for the positive and 75.9±24.4% for the negative bipolar pulses, respectively. Also, some of radiation fields having the percentage depth of the dip of more than 100% have been observed. The distribution of the depth of the dip for the positive bipolar pulses was widely extended, and the most probable depth of the dip was between 40 and 120%. Investigations conducted in Japan by Ushio et al.[18] have shown that, on average, the ratio of the opposite direction overshoot peak to theinitial peak of the bipolar pulses produced by multiple-intracloud lightning discharges was 71% for 336 positive and 59% for 129 negative pulses, respectively. The data of the present work are in roughly agreement



(a) Positive



(b) Negative

Fig. 8 Depth of the dip of the first stroke fields.

with the results obtained by Ushio et al.. Distortions in the radiations field wave shapes might be different according as whether the propagation is over land or over seawater. An erratic discrepancy may be raised by the difference in observation locations, measurement systems, geographical and seasonal conditions, and in types and natures of thunderstorms.

Figure 9 shows changes of the depth of the dip of the bipolar pulses as a function of stroke orders. All the depths of the dip for the positive bipolar pulses were somewhat greater than those for the negative and the depths of the dip for both the positive and negative bipolar pulses slowly drooped with increasing the stroke order. This result means that the bipolar pulse pattern of the radiation fields produced by intracloud lightning discharges is predominant as compared with cloud-to-ground lightning return stroke fields having 20~50% depth of the dip[24]. Also it is inferred that the bipolar pulses are the characteristics related to the breakdown processes and recombinations of the positive and negative charges in the same cloud.

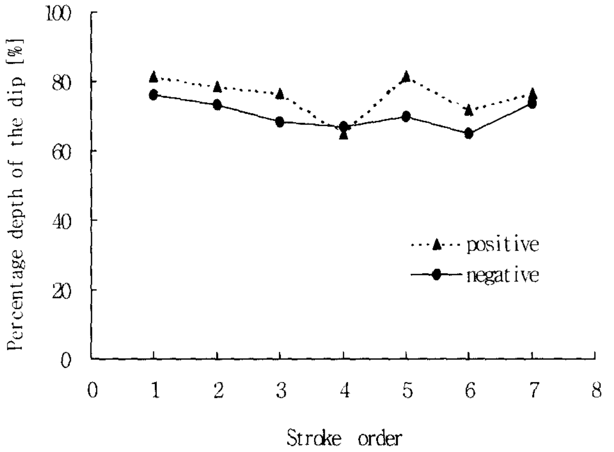
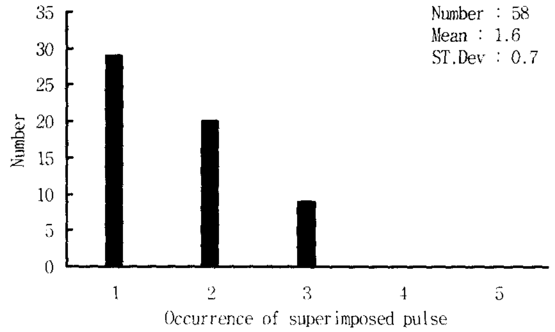


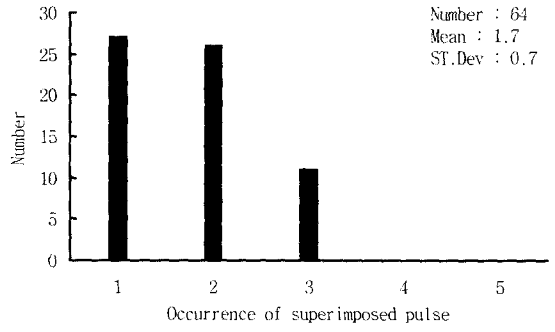
Fig. 9 Changes of the depth of the dip of the subsequent stroke fields as a function of stroke order.

3.2.4 The superimposed stepwise pulses

One or more stepwise pulses with a few microseconds were always superimposed on the initial half-cycle of the bipolar pulse of the radiation fields produced by intracloud lightning discharges. They had the peak amplitudes comparable to those of the stepped leader pulses and appeared relatively regular separations. Weidman and Krider[9] have suggested that the stepwise pulses superimposed on the initial half-cycle of the bipolar pulse are occurred by the extension of the channel in a stepped process during the primary breakdown. However unfortunately the origin of the stepwise pulses superimposed on the initial half-cycle of the bipolar pulse is still not clearly understood.



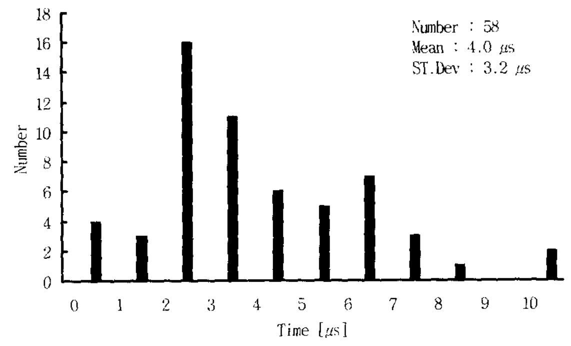
(a) Positive



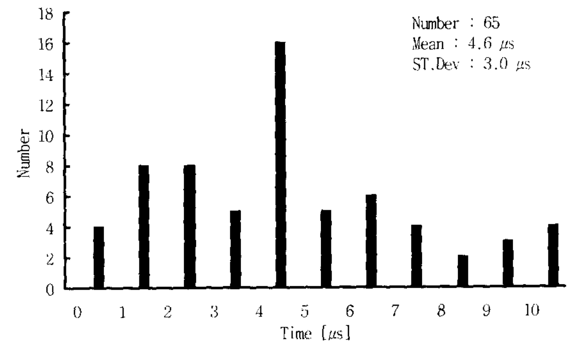
(b) Negative

Fig. 10 Histograms of the number of the pulses superimposed on the initial half-cycle of the bipolar overshoot.

Figure 10 shows the distributions of the number of the stepwise pulses superimposed on the initial half-cycle of the bipolar pulse of the radiation fields produced by intracloud lightning discharges. The numbers of the stepwise pulses superimposed on the initial half-cycle of the bipolar pulse were over the range of one through three with the mean of 1.7±0.7 for the positive and 1.8±0.7 for the negative radiation fields. There is no much difference between the observed data for both the positive and negative radiation fields. It was presented that the regular sequences of unipolar radiation pulses, which take place at 5 μs separations, are occurred in the final stage of intracloud lightning discharges in the literature[25,26]. Distributions of the time separation between the stepwise pulses superimposed on the initial half-cycle of the bipolar pulse of intracloud lightning stroke fields were summarized as shown in Fig. 11. The occurrence number and the time separations of the superimposed pulses are increased as the full width at half maximum of the bipolar pulses increases.



(a) Positive



(b) Negative

Fig. 11 Histograms of the time separations between the stepwise pulses superimposed on the initial half-cycle of the bipolar overshoot.

The time separations between the superimposed stepwise pulses were distributed within the range of less than 11 μs. The mean of the time separation between the superimposed pulses was 4.1±3.2 μs for the positive and 4.6±3.0 μs for the negative radiation fields. Also the time separations between the superimposed pulses were much less as compared to those between the stepped leader pulses. It is suggested that the origin of the stepwise pulses superimposed on the initial half-cycle of the bipolar pulse may be different from the development mechanism of the stepped leader pulses prior to the boplar pulse.[27]

4. Conclusion

Some parameters and features of the radiation fields produced by multiple-intracloud discharges were experimentally derived. The radiation fields showed a bipolar pulse peak comparable to that of lightning return stroke fields. The time separations between the subsequent strokes for both the positive and negative radiation fields decreases with increasing the number of stroke order. The ratio of the subsequent stroke peak to the first stroke peak was distributed over the wide ranges. The initial half-cycle of the bipolar pulse of the radiation fields was usually superimposed by the narrow stepwise pulses, and the time separations between the superimposed narrow pulses were in the range of less than 11 μs. On the average, the time separations between the stepwise pulses superimposed on the half-cycle of the bipolar pulse was 4.1 μs with a standard deviation of 3.2 μs for the positive and 4.6 μs with a standard deviation of 3.0 μs for the negative pulses, and the occurrence number was approximately 1.7. The present results may be useful to understand the physical properties associated with intracloud lightning discharges. Also the parameters of intracloud lightning stroke radiation fields are applicable to design a proper surge protection of electronic systems from lightning overvoltages.

References

[1] T. Ogawa and M. Brook, "The mechanism of the intracloud lightning discharge", J. Geophys. Res., 69 (1964) 5,141-5,150.

[2] X. M. Shao and P. R. Krehbiel, "The spatial and temporal development of intracloud lightning", J. Geophys. Res., Vol.101, No.D21, pp.26,641-26,668, 1996.

[3] B. H. Lee, S. H. Chang, C. H. Ahn, S. C. Lee and D. K. Jeon, "Statistical Analysis of Electric and Magnetic Fields due to Multiple Cloud Discharges", Proc. of Int. Workshop on High Voltage Engineering, Okinawa, pp.19-24, 1999.

[4] D. A. Smith, X. M. Shao, D. N. Holden, and C. T. Rhodes, "A distinct class of isolated intracloud lightning discharges and their associated radio

emissions", J. Geophys. Res., Vol.104, No.D4, pp.4,189-4,212, 1999.

[5] M. A. Uman, Lightning, Dover Pub., Inc., New York, 1984, pp.96-100.

[6] E. P. Krider, C. D. Weidman, and D. M. LeVine, "The Temperal Structure of the HF and VHF Radiation Produced by Intracloud Lightning Discharges", J. Geophys. Res., 84, No.C9, (1979) 5760-5762.

[7] V. Cooray and S. Lundquist, "On the characteristics of some radiation fields from lightning and their possible origin in positive ground flashes", J. Geophys. Res., Vol.87, o.C13, pp.11,203-11,214, 1982.

[8] J. Hojo, M. Ishii, T. Kawamura, F. Suzuki, H. Komuro, and M. Shiogama, "Characteristics and Evaluation of Lightning Field Waveforms", T. IEE of Japan, Vol. 108-B, No.4, pp. 165-172, 1988.

[9] C. D. Weidman and E. P. Krider, "The Radiation Field Wave Forms Produced by Intracloud Lightning Discharge Processes", J. Geophys. Res., Vol.84, No.C6, pp.3,159-3,164, 1979.

[10] J.R. Bils, E.W. Thomson, and M.A. Uman, "Electric field pulses in close lightning cloud flashes", J. Geophys. Res., 93, pp.15,933-15,940, 1988.

[11] Y. Villanueva, V.A. Rakov, and M.A. Uman, "Microsecond-scale electric field pulses in cloud lightning discharges", J. Geophys. Res., 99, pp.14,353-14,360, 1994.

[12] Bok-H. Lee, Kyoung-O. Lee and Bong-C. Ha, "Characteristics of Radiation Magnetic Field Waveforms Produced by Lightning Discharges", T. KIEE Trans., Vol.45, No.9, pp.1,318-1,323, 1996.

[13] Bok-H. Lee, Chang-H Ahn and Mun-N Joo, "Characteristics of the Electric Fields Associated with Lightning Discharges", T. KIEE, Vol.45, No.10, pp.1467-1472, 1996.

[14] G. Diendorfer and M. A. Uman, "An improved return stroke model with specified channel-base current", J. Geophys. Res., Vol.95, No.D9, pp.13,621-13,644, 1990.

[15] R. Thottappillil and M.A. Uman, "Comparison of lightning return-stroke models". J. Geophys. Res., Vol.98, No.D11, pp.22,903-22,914, 1993.

[16] J. C. Willett, J. C. Bailey and E. P. Krider, "A Class of Unusual Lightning Electric Field Waveforms with Very Strong High-Frequency Radiations", J. Geophys. Res., Vol.94, No.D11, pp.16,255-16,267, 1989.

[17] V.A. Rakov and M.A. Uman, "Some Properties of Negative Cloud-to-Ground Lightning Flashes versus Stroke Order", J. Geophys. Res., Vol.95, No.D5, 5,447-5,453, 1990.

[18] V. A. Rakov, M. A. Uman and R. Thottappillil, "Review of Lightning Properties from Electric Field and TV Observations", J. Geophys. Res., Vol.99, No.D5, pp.10,745-10,750, 1994.

[19] C. Guo and E. P. Krider, "The optical and radiation field signatures produced by lightning return strokes", J. Geophys. Res., Vol.87, No.C11, pp.8,913-8,922, 1982.

[20] V. A. Rakov and M. A. Uman, "Origin of lightning electric field signatures showing two return-stroke waveforms separated in time by a millisecond or less", J. Geophys. Res., Vol.99, No.D4, pp.8,157-8,165, 1994.

[21] E. M. Thomson, M. A. Galib, M. A. Uman, W. H. Beasley, and M. J. Master, "Some Features of Stroke Occurrence in Florida Lightning Flashes", J. Geophys. Res., Vol.89, No.D3, pp.4,910-4,916, 1984.

[22] S. Namasivayam, S. Lundquist and V. Scuka, "Some Characteristics of Electromagnetic Transient Waveforms from Lightning in Sweden", Proc. 20th Int. Conf. on Lightning Protection(ICLP), Interlaken, 6.5.1-6, 1990.

[23] T. Ushio, J. H. Lee, D. Wang, Z. Kawasaki, K. Matsuura, and T. Matsui, "Characteristics of Pulse Trains Superimposed on the Electric Field Changes of Japanese Winter Lightning", T. IEE of Japan, Vol.116-B, No.4, pp.453-459, 1996.

[24] M. Ishii and J. Hojo, "Statistics on Fine Structure of Cloud-to-Ground Lightning Field Waveforms", J. Geophys. Res., Vol.94, No.D11, 13,267-13,273, 1989.

[25] M. A. Uman and E. P. Krider, "A Review of Natural Lightning: Experimental Data and Modeling", IEEE Trans., Vol.EMC-24, No.2, pp.79-105, 1982.

[26] E. P. Krider, G. J. Radda, and R. C. Noggle, "Regular radiation field pulses produced by intracloud lightning discharges", J. Geophys. Res., Vol.80, No.C6, pp.3,801-3,804, 1975.

[27] B. H. Lee, S. C. Lee, C. H. Ahn, and T. Kawamura, "Physical Properties of Radiation Fields Produced by Multiple In-cloud Lightning Discharges", Jpn. J. Appl. Phys., Vol.40, Pt. 1, No.1, pp.299-306, 2001.

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