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Characterization of current pulses superimposed on the continuous current in upward lightning initiated from tall objects and in rocket-triggered lightning

Megumu Miki, Takatoshi Shindo, CRIEPI, Vladmir A. Rakov, Martin A. Uman, *University of Florida*, Gerhard Diendorfer, Martin Mair, *Austrian Lightning Detection and Information System.*, Fridolin Heidler, Wolfgang Zischank, *University of Federal Armed Forces Munich,* Rajeev Thottappillil, *Uppsala University,* Daohong Wang, *Gifu University*

***Abstract*-- We compare the characteristics of the M components and the initial continuous current pulses (ICC pulses) in natural upward lightning as observed on the Gaisberg tower (100 m), the Peissenberg tower (160 m), and the Fukui chimney (200 m) with their counterparts in rocket-triggered lightning in Florida for the clarification of the mechanism of the ICC pulses. All lightning events analyzed here effectively transported negative charge to ground. The peak, duration, risetime, half peak width and charge transfer of ICC pulses are similar to those of the M components. However, the parameters of the ICC pulses and the M components in Florida rocket-triggered lightning, except for the charge transfer, are different from those in natural upward lightning flashes. Furthermore, optical images of the ICC pulse have been obtained using video cameras. From these results, we discuss the mechanism of the ICC pulses.**

***Index Terms*-- High-speed video camera, ICC pulse, M component, Rocket-triggered lightning, Upward lightning,**

I. Introduction

Upward lightning discharges are initiated by a leader that originates from the object and propagates upward toward the charged cloud overhead (Fig. 1). Upward lightning discharges involve an initial stage (IS) that is characterized by a continuous current with a duration of some hundred milliseconds and an amplitude of some tens

Fig. 1 Still photo showing upward lightning (Fukui chimney in Japan)

to some thousands of amperes as shown in Fig. 2. In most cases, the IS contains current pulses (initial continuing current or ICC pulses) superimposed on the slowly varying continuous current. The IS is often followed by one or more downward leader/upward return stroke sequences. Since direct current measurements are usually performed on towers that experience primarily upward discharges, there has been considerable interest lately in characterizing upward lightning flashes. Specifically, there is the question of whether ICC pulses superimposed on the initial continuing current are due to return strokes or due to an M component-type lightning processes.

Current waveforms of the ICC pulses were first shown by Berger [1]. After that, several researchers compared the waveforms of the ICC pulse with those of the return stroke [2][3].

Contact Address:
Megumu Miki
Central Research Institute of Electric Power Industry
2-6-1, Nagasaka Yokosuka-shi, Kanagawa-ken, 240-0196 Japan.
E-mail: megu@criepi.denken.or.jp

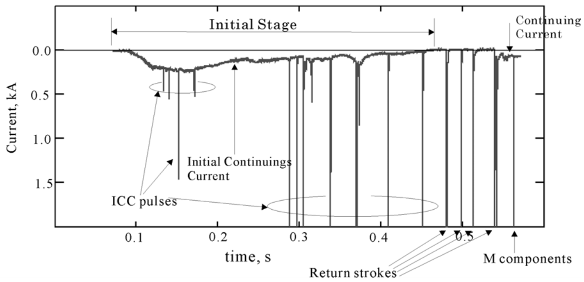

Fig. 2 Current waveform of negative upward lightning flash

These studies suggested that return stroke and ICC pulses involve different mechanisms leading to the observed differences in their characteristics. Wang et al. [4] have studied the characteristics of the ICC pulses in the initial stage (IS) of rocket-triggered lightning. A statistical comparison between these pulses and the M-component pulses superimposed on continuing currents following return strokes in triggered lightning indicates that both types of pulses are due to similar physical processes. Thus, the ICC pulses in natural upward lightning are expected to be similar to M component-type pulses. However, no quantitative confirmation of this inference is available at this time. Miki et al. [5] compared the characteristics of ICC pulses of upward lightning initiated from grounded objects with their counterparts in the Florida rocket-triggered lightning. The characteristics of the ICC pulses in object-initiated lightning are similar within a factor of two, but differ more significantly from their counterparts in rocket-triggered lightning. Specifically, the ICC pulses in object-initiated lightning exhibit larger peaks, shorter risetimes, and shorter half-peak widths than do the ICC pulses in rocket-triggered lightning. Thus, some of the ICC pulses in upward lightning appear to be different from the traditional M components.

In this international collaborative study, we compare the characteristics of the ICC pulses with their counterparts of M components in rocket-triggered lightning in Florida and in natural upward lightning as observed on (1) the Gaisberg tower (100 m, Austria), (2) the Peissenberg tower (160 m, Germany), and (3) the Fukui chimney (200 m, Japan). In the comparison of ICC pulses, the duration, peak current, risetime, half-peak width, and charge transfer of ICC pulses were compared in order to clarify the relationships between the ICC pulses and the M components.

II. DATA

The Gaisberg tower is located at the top of the Gaisberg mountain (1270 m) near Salzburg, Austria. The height of the tower is 100 m. The current was measured at the tower top, at the base of the air terminal, by a 0.25 milliohm current viewing resistor (shunt) having a bandwidth of 0 Hz to 3.2 MHz [5]. The shunt output signal was recorded by an 8 bit digitizing board (Bandwidth: 15 MHz, Memory: 16 MB) installed in a personal computer. The lower current measurement limit was 17 A.

The Peissenberg tower is located about 60 km southwest of Munich, Germany on a ridge (about 950 m above sea level) called "Hoher Peissenberg". The height of the Peissenberg tower is about 160 m. The lightning current was measured with a current transformer (Pearson CT: 0.15 Hz – 200 kHz) [5]. The signal was recorded by a digitizing oscilloscope with a storage capability of 1 million points using a sample interval of 1 μs. The lower current measurement limit was 15 A.

The Fukui chimney is part of the Fukui thermal plant on the coast of the Sea of Japan. The height of the chimney is 200 m. The current was measured by two shunts (2 milliohm and 10 milliohm) [5]. The 2 mohm shunt was used for measuring larger currents (8 - 150 kA) and the 10 mohm shunt for measuring smaller currents (0.2 - 12 kA). The shunt outputs were recorded by a 10-bit digital recorder (2M words, 100M sample/s). The lower current measurement limit was about 200 A. Optical images of the lightning discharges were observed with a high-speed digital video camera (13500 frame/sec, 128x128) and usual video camera (30 frame/sec).

The rocket-triggered lightning experiments were conducted at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Rocket launchers were located on flat ground, 20-30 m above sea level. The current was measured with a 1 milliohm current viewing resistor [5]. The signal was recorded by a tape recorder with a bandwidth from dc to 400 kHz and a noise level of approximately 20 A.

All measurement systems employed fiber optic links from the shunt (or CT) to the digital recorder. All current records in Japan and some of the current records in Germany and Austria were obtained in winter, whereas all triggered-lightning data were obtained in summer. In this paper, we used data only for negative flashes.

III. RESULTS

A. Characteristics of the ICC pulses and M components

The definitions of pulse characteristics examined in this study are as follows (Fig. 3). The peak is the difference between the peak of the current pulse and the preceding continuous current level. The duration is the time interval from the beginning of the wave front to the somewhat subjectively selected point at which the trailing edge of the current pulse becomes indistinguishable from the overall continuous current waveform. The risetime is the time interval on the wave front between the 10% and 90% values of the peak magnitude. The half peak width is the time interval between the 50% values of the peak on the wave front and on the falling portion of the pulse. The charge transfer is the charge transferred during the pulses. The continuing current level is the value of the continuing current just prior to the pulse.

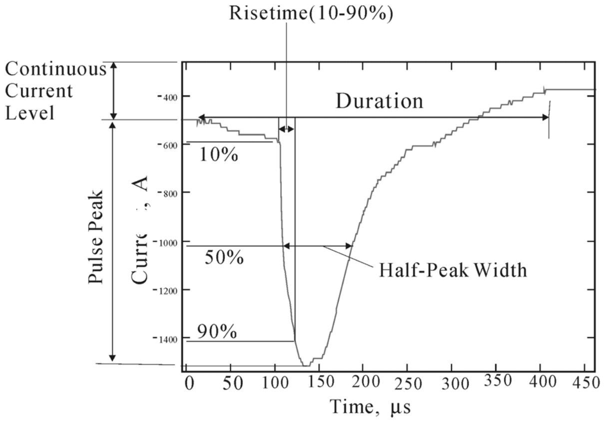

Fig. 3. Definitions of the parameters

Table l Characteristics of the pulses superimposed on the initial continuous current (ICC) and M component pulse in negative upward flashes

Experiment	Type of pulse	Sample size	Peak A	Duration ms	Rise time µs	HPW µs	CC level A	Charge transfer C
Fukui chimney (Japan)	ICC pulse	199-231	781	0.513	44.2	140.7	932	0.132
	M	28	446	0.678	66.7	184	1110	---
Gaisberg tower (Austria)	ICC pulse	344-377	377	1.20	110	276	98	0.1216
	M	127	274	1.76	236	476	---	0.167
Peissenberg tower (Germany)	ICC pulse	124	512	0.833	60.9	153	227	0.111
	M	15	645	0.819	37.4	124.8	196	0.137
Rocket-triggered lightning (Florida)	ICC pulse	247-296	113	2.59	464	943	137	0.112
	M	101-108	136	1.786	353	612	222	0.129

Table 1 gives the geometric mean (GM) values of peak, duration, risetime, half-peak width, charge transfer, and continuous or continuing current level prior to the ICC pulse or the M component, respectively in negative upward flashes. The M components are the pulses superimposed on the continuing current following a dart leader/return stroke sequence after the initial stage. In the Fukui chimney data, M components are defined as the pulses superimposed on the steady current following current pulse with a risetime of less than 10 µs and a continuing current level of less than 200 A.

In this table, the parameters of ICC pulses, except for the continuous current level, are similar to those of M components within factors of less than two in each of the three natural upward lightning. The parameters of ICC pulses are similar to those of M components in Florida rocket-triggered lightning flashes as shown by Wang et al. [4]. These results suggest that the physical processes of the ICC pulses are same as those of the M components in negative upward lightning flashes. In the previous study [5], we considered that the parameters of the ICC pulses in natural upward lightning are different from those of M components. In this study, we found that ICC pulses are similar to M components also in natural upward lightning. In the previous study, we assumed that the parameters of the M component in rocket-triggered lightning are same as those in natural upward lightning. However, it is not correct. M components in natural upward lightning exhibit a larger current peak and a shorter risetime and HPW compared to rocket-triggered lightning.

The charge transfer of ICC pulses and M components in natural upward lightning and in the Florida rocket-triggered lightning are similar to each other. This result shows that the charge transfer of the pulses superimposed on a continuing current is independent of the method of triggering the upward leader (rocket, or grounded structure), characteristics of the continuing current (initial continuous current or continuing current following a return stroke), and the geophysical conditions.

B. Characteristics of M components

Fig. 4 shows a histogram of the peak current of the M components and Fig. 5 shows the histogram of the current risetime. From these figures, we found that some of the M components in natural upward lightning exhibit the short risetime like the current waveform of return strokes. M components in Florida rocket-triggered lightning do not exhibit short risetimes and large magnitudes, as do M components in natural upward lightning. Some of the M components in both upward natural upward lightning and Florida rocket-triggered lightning exhibit a peak in the kiloampere range. Fig. 6 shows an example of current waveform of M components with a risetime of less than 2 μs. The waveform is similar to that of a small return stroke.

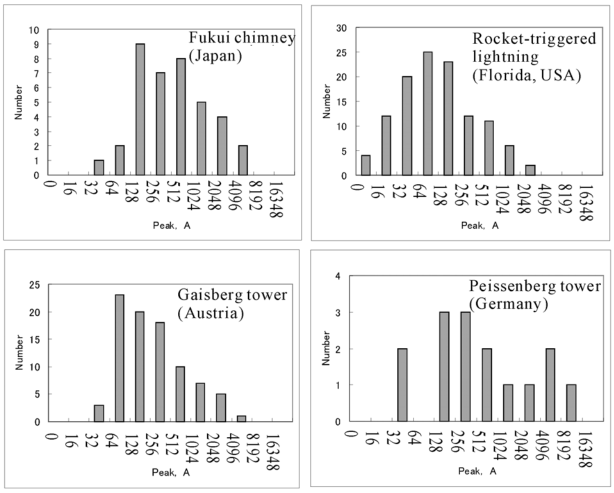

Fig. 4 The current peak of the M components

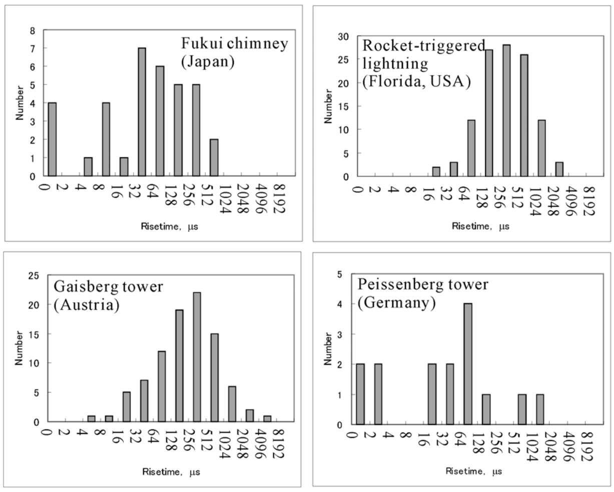

Fig. 5 The current risetime of the M components

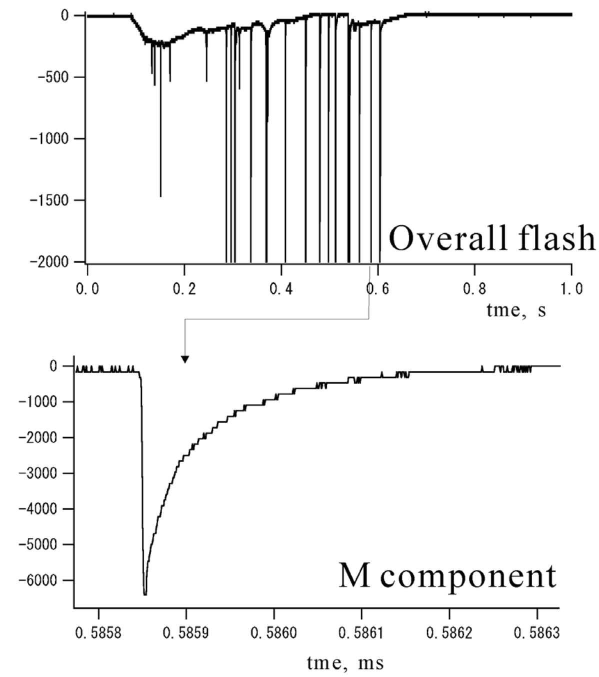

Fig. 6 Current waveform of the M component with a short risetime (< 2 μs) recorded at the Peissenberg tower in Germany.

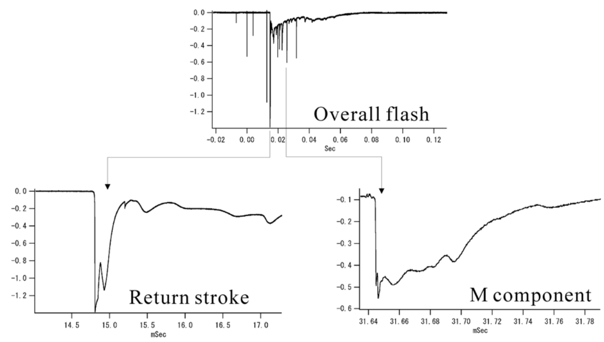

Fig. 7 Current waveforms of the return stroke and the M component (Fukui chimney in Japan).

C. Observations of the pulses superimposed on the steady current with the high-speed video camera.

We observed a upward lightning flash with a high-speed video camera and a usual video camera to clarify the relationship between the multiple upward branches and the current pulse with a short risetime. Fig. 8 shows the overall upward lightning flash obtained with the usual video camera. Figs. 9 and 10 show the current waveforms and the optical images of the ICC pulses during the upward lightning flash obtained with a high-speed video camera. In Figs. 8 and 9, there are luminous channel before the pulses. This means that the steady current flows along the channel. The current pulses with the risetime of less than 2 μs correspond to another luminous channel. These results suggest that the current pulse superimposed on the steady current with the short risetime occurs in a different upward branch than the continuing current branch.

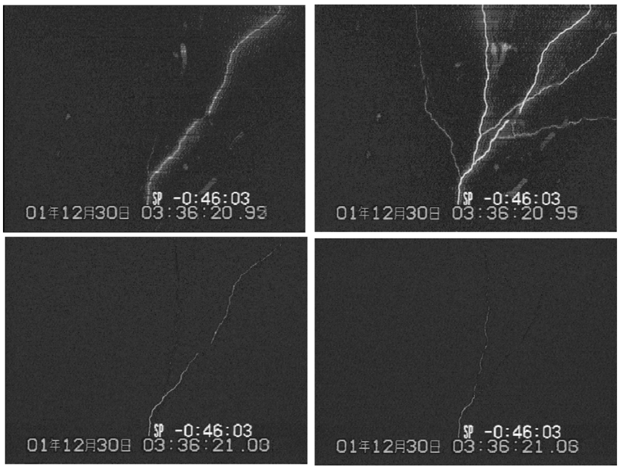

Fig. 8 Optical images of the negative upward flash (01F04) at Fukui chimney in Japan

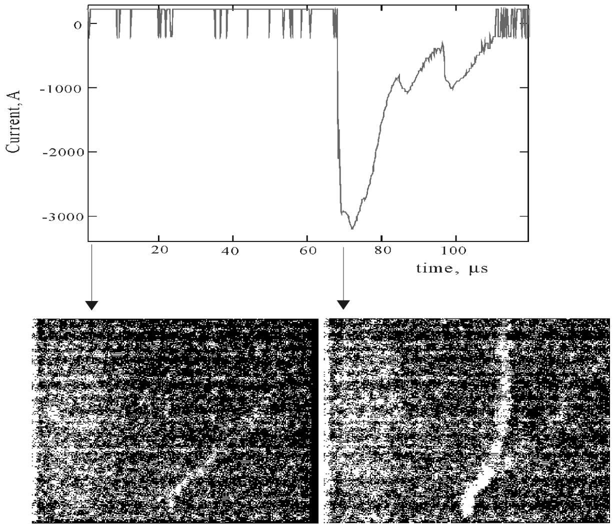

Fig. 9 Current waveform and optical images of the ICC pulse with a short risetime in upward flash (01F04).

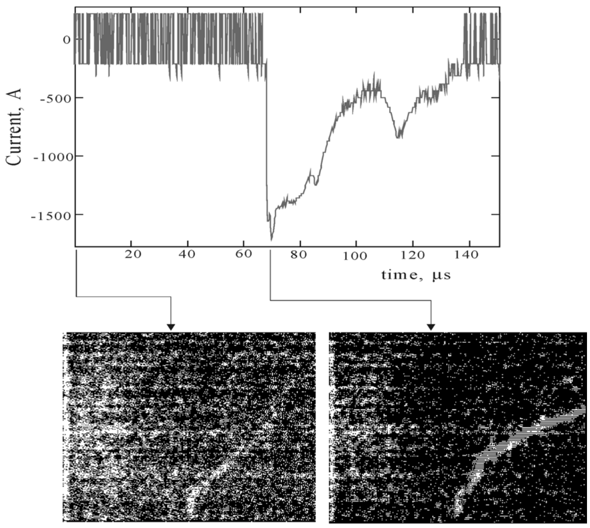

Fig. 10 Current waveform and optical images of the ICC pulse with a short risetime in upward flash (01F04)

IV. DISCUSSION:

A. The mechanism of the current pulse with a short risetime

A typical M component is characterized by a more or less symmetrical current pulse at the channel base with an amplitude of 100-200 A (2 orders of magnitude lower than that of a return-stroke current pulse), a rise time of 300-500 μs (3 orders of magnitude larger than that for a subsequent stroke) [6]. However, our analysis shows that some of M components and ICC pulses have the current peak of more than five kiloampere and the risetime of less than two microseconds. They resemble the current waveform of the return stroke. Such waveforms of M components and ICC pulses have been reported by many researchers [3][7][8]. These are comparable to smaller return strokes [9]. Furthermore, the risetime of one or two microseconds is in the range of risetimes of subsequent return strokes.

There are three modes of charge transfer to ground associated with the subsequent strokes in negative lightning discharges: (1) dart leader/return strokes, (2) continuing current and (3) M components [10]. M component and the ICC pulses occur during the continuing current in rocket-triggered lightning and natural upward lightning. The M-component mode of charge transfer requires the existence of a grounded channel carrying a current of typically some tens to some hundred of amperes, which acts as a conducting wave-guiding structure. In contrast, the dart leader/return stroke mode of charge transfer requires the absence of such a conducting path, as discussed by Fisher et al. [1]. Thus, the primary distinction between dart leader/return stroke and the M component modes is the availability of a conducting path to the ground. Thus, a return-stroke like pulse propagates along the decayed channel. The continuing current pulse propagates along a conductive channel. From these, the pulse with the short risetime and the large current peak is explained by the multiple upward branches [11]. The branches could have facilitated the simultaneous occurrence of a continuous current in one branch and a downward leader in another branch in an upward lightning flash. Fig. 11 shows schematically the mechanism of the return-stroke like pulse. First, an upward leader is initiated from the grounded structure. Second, the initial continuous current flows along one channel. Finally, the dart leader propagates along another channel. The observation results in Figs. 9 and 10 support this explanation. In these figures, the current pulse with a short risetime corresponds to the occurrence of the high luminosity channel, while the continuous current corresponds to another channel during the initial stage in the upward flash.

If the explanation is true, M components with short risetimes should only be observed in upward lightning flash.

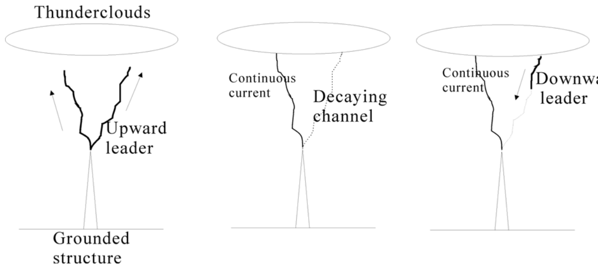

Fig. 11 Sketch of the physical mechanism of the ICC pulse with a short risetime.

B. ICC pulse and M component

The analysis show shows the parameters of ICC pulse are similar to those of M components. Thus, the physical process of ICC pulses is likely similar to that of the M components.

In particular, the GM values of the charge transfer of ICC pulse and M components in natural upward lightning flashes and in Florida rocket-triggered lightning are similar to each other within a factor of less than 2. The charge transfer of the pulse superimposed on the continuing current is between 0.1 and 0.2 C. This quantity is independent of the method of triggering the lightning, the characteristics of the continuing current and the geophysical conditions.

V. SUMMARY

We compare the characteristics of ICC pulses and M components in Florida rocket-triggered lightning and in natural upward lightning (Gaisberg tower, Peissenberg tower, and Fukui chimney). The current peak, duration, risetime, half peak width and charge transfer of ICC pulses are similar to those of the M components. However, the parameters of ICC pulses and M components in Florida rocket-triggered lightning, except for the charge transfer, are different from those in natural upward lightning flashes. Both the ICC pulses and M components in Florida rocket-triggered lightning do not exhibit short risetimes, and large magnitudes, as do ICC pulses and M components in natural upward lightning. These parameters for natural upward lightning in different geographical locations appear to be similar to each other, except for the preceding steady current level. Furthermore, the GM values of the charge transfer for the natural upward lightning and rocket-triggered lightning appear to be the similar to each other.

VI. REFERENCES

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