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Distinctive features of radiation pulses in the very first moment of lightning events

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ABSTRACT

This paper investigates the existence of distinctive features between 4 different types of lightning discharges, namely negative cloud to ground discharge (−CG), positive cloud to ground discharge (+CG), cloud discharge (IC) and isolated breakdown discharge (IB). A total of 110 very fine structure waveforms of 44 −CG, 16 +CG, 39 IC, and 11 IB discharges have been selected from a collection of 885 waveforms measured using fast electric field broadband antenna system. The measurements were carried out in Uppsala, Sweden from May to August 2010. We found that there are significant distinctions within the first 1 ms among different types of lightning discharges (−CG, +CG, IC, and IB). For example, the pulses in −CG discharges are more frequent than other discharges; the pulses in +CG discharges have the highest intensity and the IC discharge pulses tend to have shorter duration.

1. Introduction

Any lightning discharge must be initiated with an electrical breakdown process. Thus breakdown process marks a starting point of all lightning discharges. However information regarding the initiation of the breakdown process is still not really well understood. Two hypothetical mechanisms have been proposed to explain the lightning initiation process in the cloud namely the conventional breakdown theory and the runaway breakdown theory (Gurevich and Zybin, 2005).

Initial breakdown process can be defined as an in-cloud process associated with lightning initiation that involves the formation of one or more channels in random directions by bridging two charge regions. Clarence and Malan (1957) suggested that electrical discharges occur when a vertical channel bridging the main negative charge centre (*N* region) and lower positive charge pocket (*p* region). Moreover, Proctor (1997) observed vertical channels bridging the main negative and main positive charge (*P* region) sources gave rise to electrical discharge process. On the other hand, Norinder and Knudsen (1956) and Krehbiel et al. (1979) suggested that horizontal channel extended from the main negative charge source gave rise to electrical discharges. In addition, Norinder and Knudsen (1956) also observed oblique channels extended from the main charge sources.

The breakdown process during lightning initiation could be grouped into three categories as suggested by Sharma et al. (2008). Breakdown process leading to cloud-to-ground discharge (CG) return strokes is the most common and well-studied category particularly the negative CG discharges (−CG). The initial breakdown process is believed to lead the initiation of the downward-moving stepped leader. Such breakdown process is commonly known as preliminary breakdown process (PBP) in CG flash. The second category is a breakdown process associated with cloud discharge (IC) and the final category is an isolated breakdown discharge (IB) that does not lead to any subsequent activities. Nag and Rakov (2009) have used different terms to describe IB process that is attempted first cloud-to-ground leaders.

Each breakdown process associated with CG, IC, and IB consists of train of pulses with both initial half-cycle polarities (Gomes and Cooray, 2004; Sharma et al., 2008). Furthermore, Sharma et al. (2008) observed that positive initial polarity pulses generally lead to the IC and negative initial polarity pulses generally lead to the −CG. In addition, Gomes and Cooray (2004) also observed that positive initial polarity pulses generally lead to the positive CG (+CG).

Sharma et al. (2008) have made comparison of initial breakdown processes between −CG, IC and IB captured from Swedish thunderstorms. They found that it is hard to differentiate between the negative initial polarity of IB and −CG breakdown pulses. Both of IB and −CG negative initial polarity breakdown process have comparable train duration, total number of pulses and inter-pulse duration (IPD). In contrast, the negative initial polarity of IC

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breakdown pulses has higher average total number of pulses compared to IB and −CG by a factor of 1.5. On the other hand, differences of the positive initial polarity breakdown process between −CG, IC and IB could be observed. The average total number of pulses of positive initial polarity of IB breakdown pulses is smaller compared to −CG and IC by a factor of 2.5 and 3.5, respectively.

Nag et al. (2009) and Nag and Rakov (2009) provided detail comparison of initial breakdown processes between −CG, IC, and IB captured from Florida thunderstorms. They observed the existence of submicrosecond-scale pulses in both −CG and IC but none have been observed in IB. The pulse duration (PD) for the majority of the pulses in −CG (>78%) and IC (>85%) was equal or less than 4 μs. In contrast, the average PD for IB breakdown pulses was 17. This implies that the initial breakdown pulses of −CG and IC contain "narrow" or "shorter" pulses compared to IB pulses. Furthermore, the average PD of −CG breakdown pulses was longer than IC by a factor of 1.3, which implies that the initial breakdown pulses of IC are narrower or shorter than −CG. Moreover, the average total number of pulses of IC breakdown process was higher than −CG with 110.25 compared to 58.83, which means that the initial breakdown pulses of IC is not only shorter but also more compact compared to −CG.

Gomes and Cooray (2004) made a comparison of initial breakdown processes between +CG and −CG captured from Swedish thunderstorms. They discovered that the leading edges of the initial half-cycle of +CG breakdown pulses were relatively smooth compared to −CG. Typically, the initial half-cycle of the −CG initial breakdown pulses are superimposed by a few sharp, narrow, unipolar pulses. They observed that their average PD was longer than previous study, 38 μs compared to 18.8 μs (Ushio et al., 1998). Ushio et al. (1998) have considered all the pulses in the breakdown train in their analysis while Gomes and Cooray (2004) only used selected largest pulses from the breakdown train and this reason may have contributed to the different values of average PD.

In all previous studies, the analysis was based on considering the whole duration of the train of breakdown pulses, which leads to the above observations and conclusions. In this paper, we are motivated to examine the very first moment of the breakdown process (within the first 1 ms). The individual pulses in the earliest part of the train may give useful information about lightning initiation process in the cloud and give us some clue on distinctive features that may exist leading to different lightning discharge processes. Moreover, we believe that there are no studies where all four types of initial breakdown processes leading to +CG, −CG, IC and IB lightning discharges were compared in a single analysis. Sharma et al. (2008), Nag and Rakov (2009), and Nag et al. (2009) have made comparison between −CG, IC and IB only while Gomes and Cooray (2004) provided comparison between +CG and −CG only.

2. Experimentation

The measurements were done in a stationary and fully grounded van (Fig. 1) located in the premise of Ångström Laboratory, Uppsala University, Sweden (59.8°N and 17.6°E) during summer thunderstorm between 25th of May and 31st of August 2010. The measuring station is situated at about 100 km from the Baltic Sea. The measuring system consists of three main parts as shown in Fig. 2, namely the parallel flat plate antenna unit, the buffer circuit unit and the recording unit (digital storage oscilloscope or DSO).

A set of broadband antenna system (together with a buffer circuit in the protected metal case beneath the parallel plate antenna) was installed approximately 2 m away from the van and mounted about 1.5 m above the ground plane using a grounded rod as shown in Fig. 3. The antenna was used to record the fast variation of vertical electric fields. To capture fast variation field, the buffer circuit unit was designed to have around 10 ns rise time and 15 ms decay time constants. The resistor R_2 and capacitor C values shown by the circuit schematic diagram in Fig. 4 determined the value of decay time constant. The upper and lower

Fig. 1. The measurement instruments are placed within fully grounded and protective metal van.

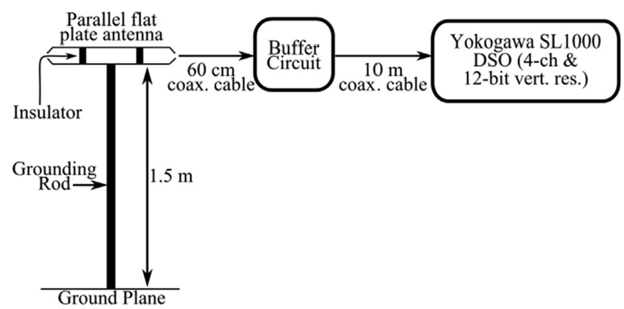

Fig. 2. The fast electric field broadband antenna system.

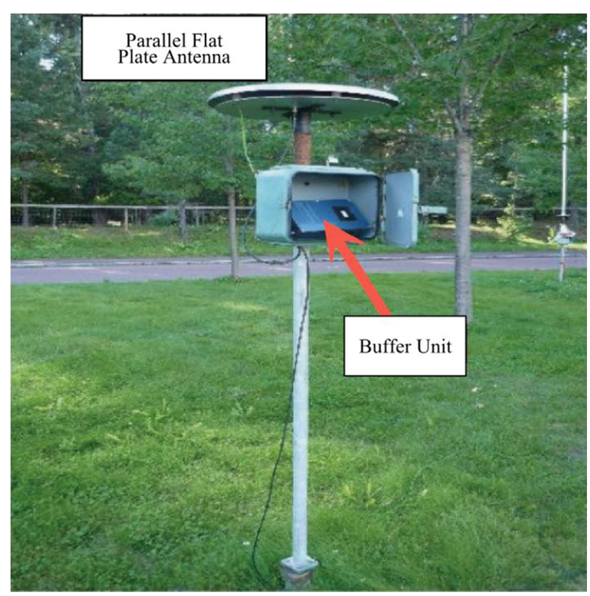

Fig. 3. Parallel flat plate antenna used for the measurement of fast electric field with the buffer circuit attached beneath it.

frequency limits are determined by the rise time and decay time constants, τ_r and τ_d, respectively. Theoretically, the higher 3 dB frequency limit of bandwidth is given by $1/2\pi\tau_r$, while for lower frequency limit of bandwidth is given by $1/2\pi\tau_d$. The rise time and decay time constants used for our measuring system are 10 ns and 15 ms, respectively. Therefore, our system translates it to 3 dB frequency limits of 10 Hz and 16 MHz. The fast variation electric field that have been acquired by the antenna are then being driven to the buffer circuit unit via a 60 cm long RG58 coaxial cable. The reasons to have the buffer circuit unit in the measurement system are to isolate the high input impedance coming from the antenna through the coaxial cable and powerful enough to send the input signal to the recording unit. Considering the sensitivity of the electronic circuits to disturbances, batteries were used to power up the buffer circuit in order to minimize interferences from other electronic devices and recording equipments.

The signal from the buffer circuit unit was directed by using a 10 m RG58 coaxial cable to the DSO, which was placed in the stationary van. The inner part of the van is half-covered with an aluminium metal plate and fully grounded. The DSO is an independent, isolated 4-channel 12-bit Yokogawa SL1000 and equipped with DAQ modules 720210 as shown in Fig. 5. The recorder's sampling rate was set to 20 MS/s (50 ns time resolution) and pre-trigger delay was 200 or 300 ms with the total of 1 s window frame. A total of 885 waveforms were recorded during this measurement campaign.

The equivalent circuit for the complete measurement system is shown in Fig. 6 where C_a is the antenna capacitance, $e(t)$ is the background electric field, h_e is the effective height (or effective length) of the antenna, C_c is the cable capacitance, R_1 is the cable resistance, C is the capacitance used to set the decay time constant, R_2 is the resistance that also used to set the decay time constant, R_o and C_v are the resistance and capacitance used to match with buffer output impedance and coaxial cable to recording unit, V_m is the measured voltage at the oscilloscope and R_m is the matching resistor for the coaxial cable connection to the oscilloscope.

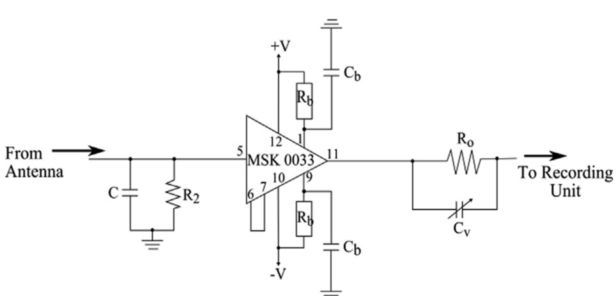

Fig. 4. The schematic diagram of the buffer electronic circuit.

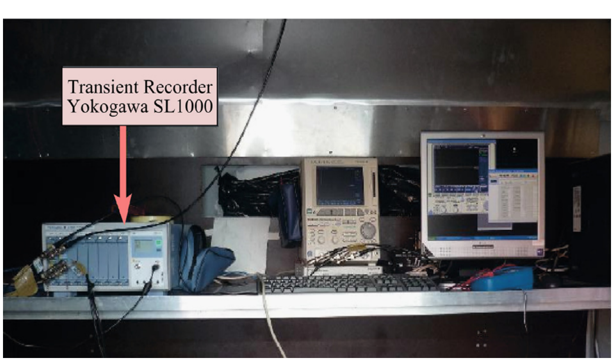

Fig. 5. The recording unit placed in the van.

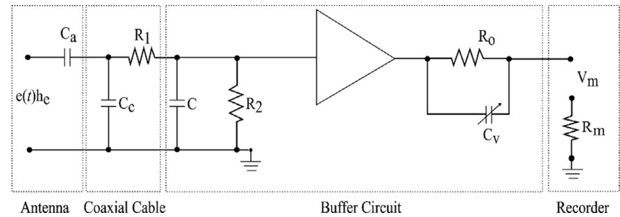

Fig. 6. Equivalent circuits for the fast electric field broadband antenna measuring system.

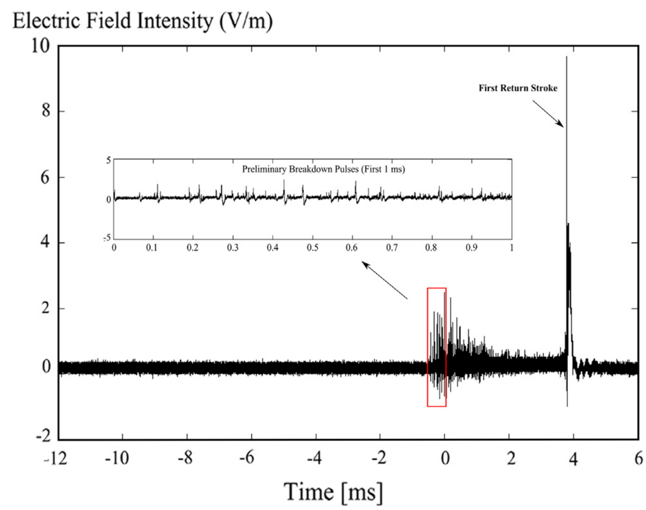

Fig. 7. Activity recorded on 24 August 2010, trace number 30 at 15:41:41, the time window during this measurement was 1 s with pre-trigger delay of 300 ms. As is seen, activity consists of a return stroke and the expanded part which is the first 1 ms of the breakdown pulses that leads to negative CG discharges (−CG).

3. Data

A total of 885 waveforms were recorded and examined during this campaign. Out of these 110 waveforms of very fine structure were selected and these were then divided into a particular category. 44 out of 110 were −CG, 16 were +CG, 39 were IC, and the remaining 11 waveforms were IB. The analysis was focusing on the pulses found from the initial breakdown process for the first 1 ms duration. Figs. 7–10 show an example of the first 1 ms of preliminary breakdown pulses extracted from −CG, +CG, IC and IB discharges, respectively.

The selected waveforms must be processed before they can be analyzed. The step-by-step data processing of the selected waveforms are explained below:

Step 1. *Filtering*
The waveforms were filtered with a first order 2 kHz high pass filter in order to eliminate lower frequency and static field components.*Step* 2. *Waveform inversion (IC and* +*CG only)*
This particular step was done only for IC and +CG waveforms. This is because both waveforms have polarities opposite to −CG and IB. The inversion of the waveforms was done using Matlab before zeroing it to the offset level.*Step* 3. *Zeroing the offset level*
During the measurement, it often occurred that the captured waveforms were displaced from zero or reference line due to low battery voltage supply. The waveforms were moved to the zero reference line based on the offset value. The waveform-offset value was determined visually from Xviewer waveform reader and a horizontal line was dragged either up or down to

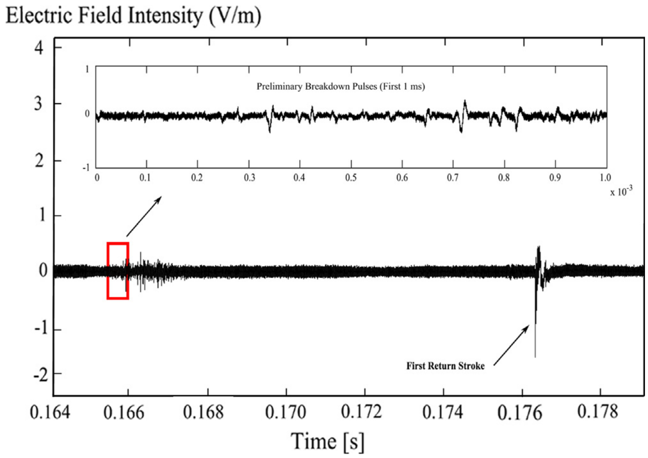

Fig. 8. Activity recorded on 28 August 2010, trace number 12 at 17:17:58, the time window during this measurement was 1 s with pre-trigger delay of 200 ms. As is seen, activity consists of a return stroke and the expanded part which is the first 1 ms of the breakdown pulses that leads to positive CG discharges (+CG).

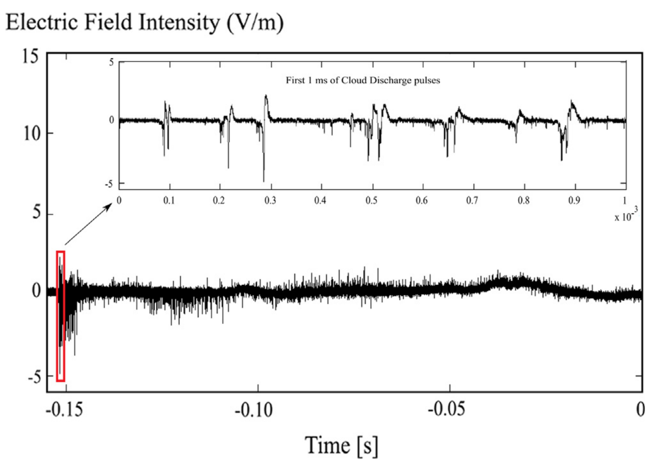

Fig. 9. Activity recorded on 24 August 2010, trace number 31 at 15:43:38, the time window during this measurement was 1 s with pre-trigger delay of 300 ms and the expanded part which is the first 1 ms of the breakdown pulses that lead to cloud discharge (IC).

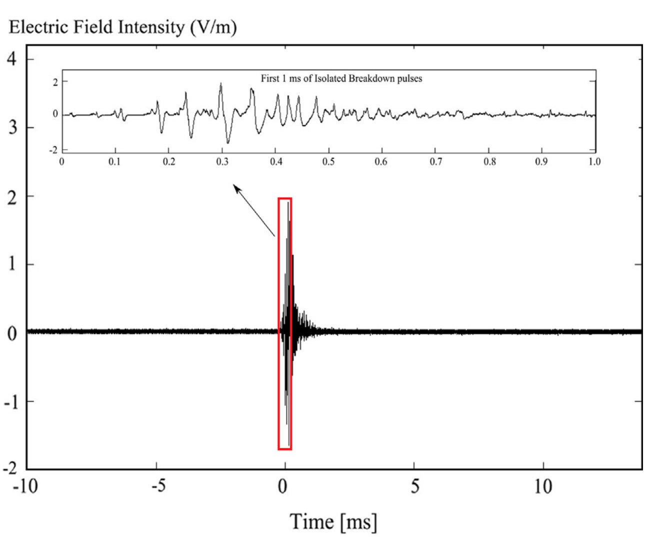

Fig. 10. Activity recorded on 25 August 2010, trace number 15 at 13:54:40, the time window during this measurement was 1 s with pre-trigger delay of 200 ms. As is seen, no further activity is found after the isolated breakdown and the expanded part which is the first 1 ms of the isolated breakdown pulses (IB).

get the best reference or zero crossing line in the middle of the waveform.

Step 4. *Categorization method*

Pulse categorization method (Ahmad et al., 2010) was applied in order to choose an appropriate starting point of the first 1 ms. All pulses in a waveform were grouped into 3 different categories; large (L), medium (M) and small (S). Within the first 1 ms, 5 pulses with the largest amplitudes were selected and averaged. This average value was then used to group the pulses. The definitions of each category are as follows:

i. Large category (L): the amplitude of the pulse is more than or equal to 50% of average value.
ii. Medium category (M): the amplitude of the pulse is between 25% and 49% of the average value.
iii. Small category (S): the amplitude of the pulse is between 12.5% and 24% of the average value.

If the noise was dominant where the calculated S category value was lower than noise level, then the noise level would become the S category value.*Step* 5. *Definition of the first pulse of* 1 *ms duration*

The manual visual scanning to get the first pulse began from the left of the waveform. If the amplitude of the first detected pulse was lower than S category value, the scanning continued to the next pulse. Once the amplitude of the pulse was in the S category value, that pulse was marked as the first pulse. The 1 ms duration began with this first pulse.*Step* 6. *Total number of pulses*

Each pulse has a starting point and an end point relative to the reference line as shown in Fig. 11. The total number of pulses in the first 1 ms duration was counted for each waveform and would be used to estimate the average of normalized amplitude later.*Step* 7. *Amplitude normalization*

In each waveform, a pulse with the largest amplitude was chosen as a reference pulse. Then the amplitude of the remaining pulses was normalized to the reference pulse. Since we do not know the distance between the lightning source and the point of observation, amplitude normalization would help us to analyze the waveform amplitude pattern, relative to the largest amplitude. Finally, the normalized amplitudes were averaged to the total number of pulses for each waveform.*Step* 8. *Pulse duration (PD)*

Pulse duration is the duration of one complete cycle. When the pulse amplitude was higher than S category value, we defined the start point and the end point as shown in Fig. 11.

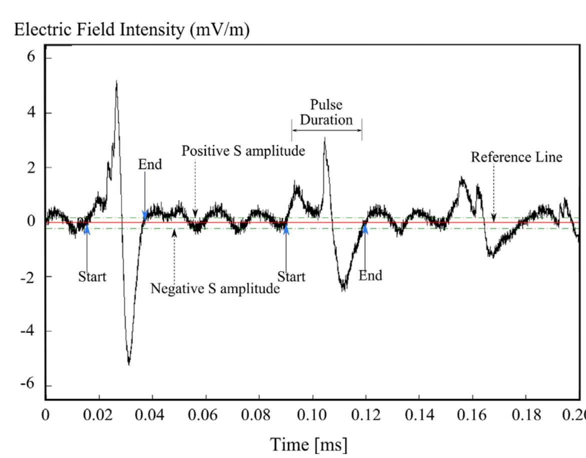

Fig. 11. Waveform characterizations. (*Note*: Green dotted lines show the small amplitude S category for both polarities and red solid line shows the reference line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Results and discussions

The statistical distribution of the total number of pulses, the average normalized amplitude, and the pulse duration are given for all four different categories as side-by-side box plots in Figs. 12–14, respectively. The plots in Fig. 12 suggest that it is almost impossible to differentiate between +CG, IC, and IB groups. They have very close mean and Standard Deviation (SD) values, which gives us an idea that they are almost indistinctive. The only significant distinction could be made is by −CG group where the mean value of −CG is significantly higher than the others. The plots in Figs. 13 and 14 indicate the same pattern due to the very same reason. The only significant distinction could be made in Fig. 13 is by +CG group where the mean value of +CG is significantly higher than other three. Furthermore the only significant distinction could be made in Fig. 14 is by IC group where the mean value of IC is one third from IB mean value and less than half from −CG and +CG values. The complete statistical distribution information can be obtained from Table 1.

Each parameter indicates different significant distinctive group. The total number of pulses suggests that −CG is significantly distinctive from the others while average of normalized amplitude suggesting +CG to be significantly distinctive instead of −CG. On the other hand, PD parameter suggests that IC is more distinctive compared to the others. However, if we consider that much longer PDs of −CG, +CG, and IB groups were affected by propagation over land, it is possible that we cannot observe any distinction between the groups. As we do not have distance information to relate this possibility, we are not in the position to comment further about the effect of propagation over land.

The basis of the claim that these groups are significantly distinctive is their mean values differ a lot from the others, which makes sure that they are not overlapping (individual data are less overlap) or at least the overlapping percentage is small. The Analysis Of VAriance (ANOVA) statistical test was used to test if the groups have the same mean values or not as have been used by Ahmad et al. (2010). ANOVA test is the best statistical tool to be used in order to compare more than 2 groups and having the unbalance sample numbers (Gravetter and Wallnau, 2007). Summary of ANOVA test results is tabulated in Table 2 below.

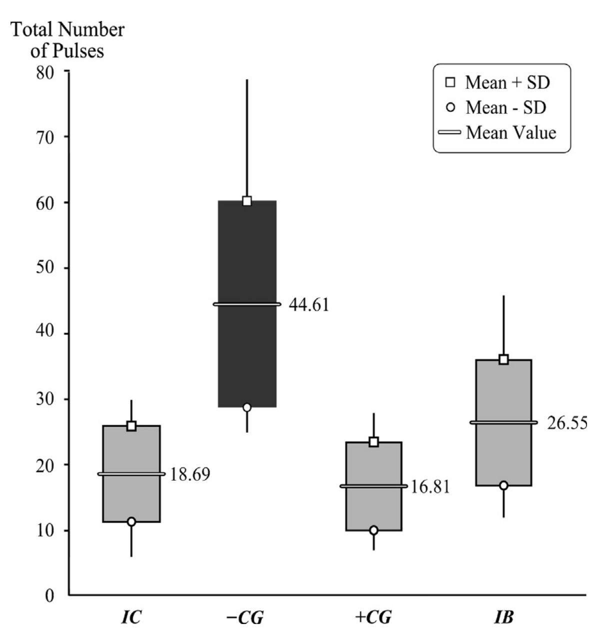

Fig. 12. Statistical distribution of the total number of pulses for IC, −CG, +CG and IB groups.

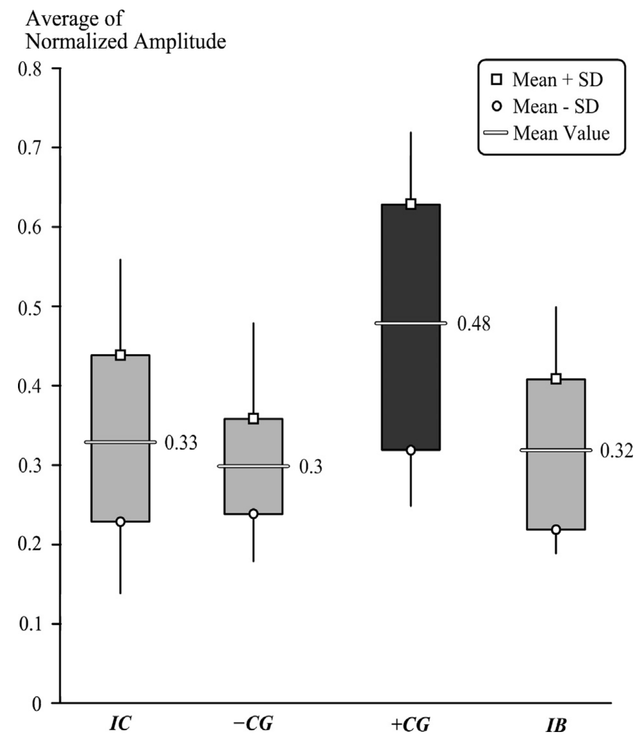

Fig. 13. Statistical distribution of the averaged normalized amplitude for IC, −CG, +CG and IB groups.

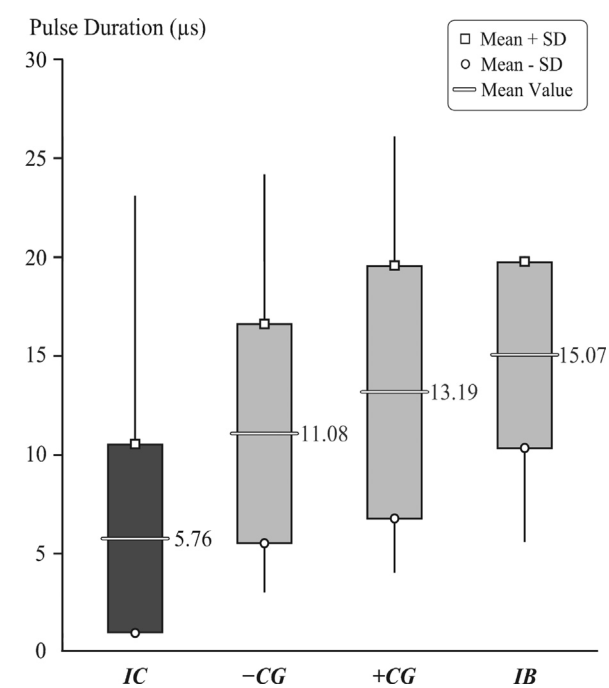

Fig. 14. Statistical distribution of the pulse duration (PD) for IC, −CG, +CG and IB groups.

From Table 2, *P*-value and *F*-value for all parameters are much less than α and are much higher than F_{critical} value, respectively. These results tell us that all four lightning groups are significantly distinctive to some extent. The correlation coefficient (ω^2) gives us an idea about how strong the magnitude of distinction between groups are and the calculated values are 53.15%, 25.60%, and 26.04% for the total number of pulses, average normalized amplitude, and pulse duration respectively.

A post-hoc multiple-comparison Tukey statistical test was chosen to evaluate the distinction level between two groups given significance levels α equal to 95% and 99%. If we have 4 groups that means there are 6 pair-wise combinations. In this test, it finds the differences between the mean values of all groups and then this difference value is compared to a critical value so called honestly significant difference (HSD) to see if the difference is significant.

From Table 3, the total number of pulses parameter suggests that there is significant distinction with 99% confidence level between −CG and the other groups. Also there is significant distinction with 95% confidence level between +CG and IB. Interestingly, IC cannot be differentiated significantly from other groups except with −CG. The average of normalized amplitude parameter suggests that there is significant distinction with 99% confidence level between +CG and the other groups. Moreover, −CG, IC, and IB cannot be differentiated significantly except with +CG. The pulse duration parameter suggests that there is significant distinction between IC and the other groups. Moreover, −CG, +CG, and IB cannot be differentiated significantly except with IC. Therefore we can summarize that, the total number of pulses parameter can be used to differentiate between −CG and other groups significantly, the averaged of normalized amplitude parameter can be used to differentiate between +CG and other groups significantly, and the pulse duration can be used to differentiate between IC and other groups significantly.

These findings through statistical test mean tell us that the initial breakdown mechanism of each type of discharges is different. The −CG discharge has the total number of initial pulses that is significantly distinctively higher from other discharges. We suggest that the −CG discharge tends to radiate pulses more frequently in the initial stage when compared to other discharges. Our finding contradicts the observations made by Sharma et al. (2008) and Nag et al. (2009) where they suggested IC discharge tends to radiate pulses more frequently. This contradiction may be due to the fact that they analyzed the whole train of pulses while we focusing our analysis only within the first 1 ms of the train. The +CG discharge could be differentiated from −CG and the other discharges by observing the average normalized amplitude parameter. We suggest that the +CG discharge tends to radiate pulses with higher electric field intensity compared to other discharges.

Table 1
Complete statistical distribution information for IC, −CG, +CG and IB groups.

Group	Statistics	Total number of pulses	Averaged normalized amplitude	Pulse duration (μs)
IC	Arithmetic mean	18.69	0.33	**5.76**
	Geometric mean	17.11	0.31	4.36
	Median	17	0.33	4.19
	Standard deviation, σ	7.32	0.10	4.79
−CG	Arithmetic mean	**44.61**	0.3	11.08
	Geometric mean	41.86	0.29	9.79
	Median	44	0.3	9.67
	Standard deviation, σ	15.82	0.06	5.62
+CG	Arithmetic mean	16.81	**0.48**	13.19
	Geometric mean	15.49	0.45	11.59
	Median	16	0.52	11.365
	Standard deviation, σ	6.75	0.15	6.41
IB	Arithmetic mean	26.55	0.32	15.07
	Geometric mean	26.82	0.29	13.68
	Median	27	0.31	15.37
	Standard deviation, σ	8.78	0.08	4.70

Table 2
Summary of ANOVA statistical test results for different temporal parameters.

Parameter	***P*-value**	***F*-value**	**Correlation coefficient, ω^2 (%)**	**Remarks**
$\alpha=0.05$ $F_{critical}=2.69$				If $P<\alpha$ and $F \geq F_{critical}$, we reject the null hypothesis and the mean is different between groups, otherwise we accept the null hypothesis
Total number of pulses	3.9E−18	42.59	53.15	
Average of normalized amplitude	1.4E−07	13.62	25.60	If *F*-value and ω^2 are higher, the distinction variations between groups are more coherent
Pulse duration	1.0E−7	13.91	26.04	

Table 3
Summary of post-hoc Tukey test.

Parameters		**−CG and +CG**	**−CG and IC**	**−CG and IB**	**+CG and IC**	**+CG and IB**	**IC and IB**
Total number of pulses	$HSD_{0.05}=9.61$ and $HSD_{0.01}=11.73$						
	Group mean difference	27.8	25.92	18.06	1.88	9.74	7.86
	P-value condition	< 0.01	< 0.01	< 0.01	Not significant	< 0.05	Not significant
	Confidence level	99	99	99		95	
Average of normalized amplitude	$HSD_{0.05}=0.08$ and $HSD_{0.01}=0.1$						
	Group mean difference	0.18	0.03	0.02	0.15	0.16	0.02
	P-value condition	< 0.01	Not significant	Not significant	< 0.01	< 0.01	Not significant
	Confidence level	99			99	99	
Pulse duration	$HSD_{0.05}=4.43$ and $HSD_{0.01}=5.41$.						
	Group mean difference	2.11	5.32	3.99	7.43	3.99	9.31
	P-value condition	Not significant	< 0.05	Not significant	< 0.01	Not significant	< 0.01
	Confidence level		95		99		99

From here we can deduce that −CG radiates pulses more frequently than +CG but with much lower intensity in the first 1 ms duration. Furthermore, the IC discharge also could be differentiated significantly from −CG, +CG, and IB by observing the pulse duration parameter. We suggest that IC discharge tends to radiate shorter pulses when compared to the others, which is in perfect agreement with observations by Nag et al. (2009). Also we suggest that IC discharge tends to radiate less frequent compared to −CG and much lower intensity when compared to +CG.

In the light of recent optical radiation and electric field studies, the leader velocity during the initial stage of breakdown process in −CG discharge is much faster than the later stage of breakdown process as evidence from Fig. 2 in Campos and Saba (2013). In the initial stage, the velocity has dropped drastically from 1.2×10^6 m s^{-1} to 6×10^5 m s^{-1} along the 800 m leader channel in just 1 ms. Further evidence from Table 3 in Stolzenburg et al. (2013) shows that the velocity of the first leader channel (corresponds to the first electric field breakdown pulse) is much faster than the subsequent leader channels extension (subsequent electric field breakdown pulses). The average velocity of the first leader channel is estimated at 1.09×10^6 m s^{-1}, much higher than the average velocity of the second leader channel extension at 7.8×10^5 m s^{-1}. Stolzenburg et al. (2013) has inferred that very fast leader channel extension during the initial stage of −CG was due to very rapid impulsive breakdown processes. Consequently, we infer that the initial stage of breakdown process in −CG discharge is temporally more compact with radiation pulses than the later stage based on the fact that very rapid impulsive breakdown processes radiated large number of breakdown pulses during the initial stage. This inference may explain why we found that −CG discharge has the total number of pulses that is significantly distinctively higher from other discharges in the first 1 ms. On the other hand, this inference also suggesting that the ionizations during breakdown process of IC, +CG, and IB discharges were less rapid when compared to −CG discharge. Furthermore, recent finding based on wavelet analysis by Esa et al. (2013) shows that the first electric field pulse of IC discharge radiates higher frequency component when compared to the other discharges. They suggested that the PD of the first electric field pulse of IC discharge must be much shorter than the other discharges, which supported our observation about PD of IC pulses within the first 1 ms.

5. Conclusion

We found that there are significant distinctions between all the lightning discharge groups (−CG, +CG, IC, and IB) within the first 1 ms of the electrical breakdown process. The −CG radiates pulses more frequently than other discharges with much lower intensity when compared to +CG in the first 1 ms duration. The +CG always radiates the highest intensity pulses compared to other discharges. The IC discharge tends to radiate shorter pulses but less frequent compared to −CG with much lower intensity when compared to +CG.

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References

Ahmad, N.A., Fernando, M., Baharudin, Z.A., Rahman, M., Cooray, V., Saleh, Z., Dwyer, J.R., Rassoul, H.K., 2010. The first electric field pulse of cloud and cloud-to-ground lightning discharges. J. Atmos. Sol. Terr. Phys. 72, 143–150.

Campos, L.Z.S., Saba, M.M.F, 2013. Visible channel development during the initial breakdown of a natural negative cloud-to-ground flash. Geophys. Res. Lett. 40, 1–6, http://dx.doi.org/10.1002/grl.50904.

Clarence, N.D., Malan, D.J., 1957. Preliminary discharge processes in lightning flashes to ground. Q. J. R. Meteorol. Soc. 83, 161–172.

Esa, M.R.M., Ahmad, M.R., Cooray, V., 2013. Wavelet analysis of the first electric field pulse of lightning flashes in Sweden. Atmos. Res. (http://dx.doi.org/10.1016.j.atmosres.2013.11.019)

Gomes, C., Cooray, V., 2004. Radiation field pulses associated with the initiation of positive cloud to ground lightning flashes. J. Atmos. Sol. Terr. Phys. 66, 1047–1055.

Gravetter. Frederick J., Wallnau, Larry B., 2007. Introduction to Analysis of Variance, Statistics for the Behavioural Sciences. Thomson Wadsworth, pp. 392–397.

Gurevich, A.V., Zybin, K.P., 2005. Runaway breakdown and the mysteries of lightning. Phys. Today 58 (5), 37, http://dx.doi.org/10.1063/1.1995746.

Krehbiel, P.R., Brook, M., McCrory, R., 1979. An analysis of the charge structure of lightning discharges to the ground. J. Geophys. Res. 84, 2432–2456.

Nag, A., Rakov, V.A., 2009. Electric field pulse trains occurring prior to the first stroke in negative cloud-to-ground lightning. IEEE Trans. Electromagn. Compat 51 (1), 147–150.

Nag, A., DeCarlo, B.A., Rakov, V.A., 2009. Analysis of microsecond- and submicrosecond-scale electric field pulses produced by cloud and ground lightning discharges. Atmos. Res. 91, 316–325.

Norinder, H., Knudsen, E., 1956. Pre discharges in relation to subsequent lightning strokes. Arkiv foer Geofysik 2 (27), 551–571.

Proctor, D.E., 1997. Lightning flashes with high origin. J. Geophys. Res. 102, 1624–1693.

Sharma, S.R., Cooray, V., Fernando, M., 2008. Isolated breakdown activity in Swedish lightning. J. Atmos. Sol. Terr. Phys. 70, 1213–1221.

Stolzenburg, M., Marshall, T.C., Karunarathne, S., Karunarathna, N., Vickers, L.E., Warner, T.A, Orville, R.E., Betz, H.-D., 2013. Luminosity of initial breakdown in lightning. J. Geophys. Res. Atmos. 118, 2918–2937, http://dx.doi.org/10.1002/jgrd.50276.

Ushio, T., Kawasaki, Z., Matsu-ura, K., Wang, D., 1998. Electric Fields of Initial Breakdown in Positive Ground Flash. American Geophys. Union, Paper no. 97d01975–0148-0227/97/97JD-01975.