Power Spectrum Density Analysis of Intra-Cloud Lightning Discharge Components from Electric Field Recordings in Poland

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Abstract—The aim of this paper was to show usefulness of Power Spectrum Density analysis for identification of different components of IC lightning. We have presented some exemplary pulse train electric field recordings characterized for the specific time development of intra-cloud lightning discharges observed during summer thunderstorms in Poland. These data were gathered by two detection stations working independently in Warsaw and Rzeszow. Both stations are based on triggered electric field acquisition in the ELF-MF frequency range. Such recorded electric field courses of intra-cloud lightning were then analyzed both in the time domain and in the time-frequency domain with application of the short-time Fourier transform (STFT). On the basis of the used STFT procedure the Power Spectrum Density (PSD) spectrograms were computed. This whole computer procedure was performed by using the Matlab platform. Due to that we were able to distinguish some different intra-cloud lightning components as the preliminary breakdown stages including sequences of initial pulse bursts, K- and J-type electric field changes and sometimes even a trace of the Narrow Bipolar Pulses (NBP’s). We have obtained different shape/pattern of the particular PSD stripes related/corresponding to the considered components of intra-cloud lightning. Summarizing of our PSD analysis of the recorded intra-cloud lightning incidents we have noticed that the PSD stripe structure of the initial breakdown processes for in-cloud and cloud-to-ground lightning is similar. But, the characteristic and different shape of the PSD stripe was obtained for the K-type electric field changes occurring during intra-cloud lightning. For these cases the PSD stripes were of the same height and width as for the return stroke incidents from the cloud-to-ground flash, but their intensity for the frequencies above 500 Hz was much lower. On the other hand, the PSD stripe obtained for the NBP was very often the strongest one and therefore it was hard to be properly distinguished in contrast to the return stroke stage from the cloud-to-ground flash.

Keywords: in-cloud lightning discharge; preliminary breakdown; K-change; J-change; narrow bipolar pulse; short-time Fourier transform; power spectrum density

I. INTRODUCTION

The analysis of electric field (E-field) changes associated with the occurrence of in-cloud (IC) lightning is much more difficult than that one for cloud-to-ground (CG) strokes. To scrutinize the time development of a complex E-field change structure IC lightning the used measurement hardware should be characterized by the wide bandwidth and to have the upper frequency limit as high as possible. We know now from the literature [1] that any IC discharge is consist from two stages, i.e., the early (active) stage and the late (final) one. The typical early stage lasts from some tens to hundreds of milliseconds and usually comprises characteristic E-field changes such as: the train of preliminary breakdown pulses, often with some NBP events, and the sequence of consecutive so-called K-changes that are separated by J-changes. This stage can be also identified as that one involved in the time development and a space extension of the bidirectional leaders of the following numerous IC strokes. These positive and negative leaders develop themselves, respectively through negative and positive electric charge adjacent cloud pockets. A loss of the connection between these leaders begins the so-called J-change of E-field, during which a new part of negative electric charge is transported to the IC lightning origin from more remote negatively charged regions in the cloud. Such stage (final stage) can obey of several J-changes and continues from tens to hundreds of milliseconds.

The preliminary breakdown (PB) stage as an initial process of lightning channel development is common for both CG and IC lightning discharges. The reason that it is not always visible in the performed ground level electromagnetic (EM) field recordings can be resulted from a limited sensitivity of the used E-field sensor, or by too large distance from it to the considered lightning source [2]. Thus, to record properly any PB stages we need to disposal a relatively fast ADC recording unit and an E-field antennae having the bandwidth up to several MHz. Farther investigation of E-field changes connected with the PB stage is essential issue for better understanding how some processes of the initiation of IC or CG lightning discharge can occur/follow in different regions of the thundercloud. There are many reported cases in the literature [2,3,4], when the EM peaks occurring during the PB stages have been comparable, or even larger than the following E-field change associated with the first RS of the considered CG flash. Such high amplitude PB pulses are often recognized
as being the NBP events. On the other hand, the rising times of the PB E-field pulses are greater than for other major components of lightning discharge. This can be very dangerous for any electronic device that is too close to the PB lightning sources, e. g. for an aircraft passing near a thundercloud. Furthermore E-field analysis of the PB lightning stages is also important to elaborate the relevant overvoltage and lightning protection rules that should be used by us in all circumstances.

Despite that the numerous IC lightning are well documented in literature [1] there are still many unknown factors with regard to the initiation and development of these natural electric discharge processes. For instance, there is a lack of the PSD analysis of such lightning incidents that can give some valuable information about frequency characteristics of their PB, NBP’s, or K- and J-changes [5,6,7]. Many engineering models of lightning channel applied in lightning protection techniques are only based on considerations in the frequency domain of the associated E-field changes [8,9,10]. Hence, the frequency parameters of IC lightning estimated from their PSD analysis can be useful to overcome some difficulties of the effective EM noise elimination by the used overvoltage protection technique and which are not resolved sufficiently as yet.

II. LIGHTNING ELECTRIC FIELD MEASUREMENT SETUPS

Our PSD analysis of IC lightning incidents was based on their E-field signatures recorded on the ground level. Such recordings were obtained from two detection stations working independently in Warsaw and Rzeszow [Fig.1].

The Warsaw station is a part of the greater system called the Local Lightning Detection Network (LLDN) [11]. The whole LLDN is consisted of six measuring stations. But currently only a few stations are working continuously. On the other hand, the Rzeszow station is a relatively new lightning research site [12,13] and it has been developed on basis of the experience gained from the previous LLDN activity in Warsaw region during thunderstorm seasons. Both measuring stations were equipped in similar E-field sensor working in the ELF-MF frequency range.

The only one difference between them is that the Warsaw E-field antenna frequency bandwidth is from 5 Hz to 1 MHz and for the Rzeszow one its frequency band is from 0.5 Hz up to 3 MHz. Thus, for the context of this paper all E-field records obtained from the Rzeszow station are named as the fast E-field recordings. Additionally, the Rzeszow station was equipped with one E-field mill which is able to record the slow component of E-field changes of passing thunderstorm from 0 Hz up to 10 Hz. All our E-field lightning signatures are UTC synchronized with the same 1-µs time precision.

The sampling frequency performance of the ADC unit used in the Warsaw station is the 50 kS/s and in the Rzeszow one it is the 25 MS/s. In order to compare results from both stations the recordings obtained in the Rzeszow station were resampled to the 50 kS/s, when it is necessary. Both systems were intentionally designed to detect mainly RS incidents from CG flashes. Hence, their triggering circuits have the internal built-in selective 10 kHz filters which are dedicated to pass only the

III. THE PSD ANALYSIS OF DIFFERENT E-FIELD SIGNATURES OF IN-CLOUD LIGHTNING

The Power Spectrum Density analysis was done on the basis of the short-time Fourier transform [14,15] applied to E-field recordings of lightning discharge incidents. The PSD magnitude is proportional to the square of the amplitude of E-field intensity and therefore it can be also related to the power of lightning electromagnetic (EM) wave. It is assumed that such wave is only composed of the radiation component [16]. This condition is fulfilled when our lightning E-field recordings are gathered from distant lightning, i. e., remote about several tens of kilometers from the measuring site [1]. All parameters of the STFT procedure used for the PSD analysis are given in each spectrogram panel presented in Figs. 2-5. In several selected cases of IC flashes recorded by the Rzeszow station their E-field lightning waveforms were resampled from 25 MS/s to 50 kS/s in order to fit them to the
similar E-field IC lightning recordings from the Warsaw station and to perform some comparisons with results of the previous PSD analysis for CG flashes [6,7]. The primary parameter set of the obtained PSD spectrograms for the considered IC lightning was chosen as follows: the STFT window consists of 128 samples, the overlap is equal to 120 samples and the FFT length is equal to the STFT window. Due to that it was possible to obtain the appropriate compromise between the proper choice of the frequency range and the time resolution for the PSD spectrogram display of the considered IC lightning incidents. On the other hand, the PSD spectrograms obtained with the sampling of 25 MS/s were related to the fastest E-field components of the recorded lightning incidents. In contrast to the Warsaw station, the E-field antennae used in the Rzeszow site is not calibrated laboratory as yet. Thus, its comparative calibration was performed on the basis of comparison several lightning strokes detected by the Rzeszow station with these ones simultaneously reported by the LINET system [17]. Therefore the calibration coefficient $k$ can be estimated according to the expression (1) using the form of the Biot-Savart relation given in [18] as follows:

$$k = \frac{E_{\text{MAX}}}{E_{\text{ADC}}} = \left(\frac{c_{\text{RS}}\mu_0 I}{2\pi R E_{\text{ADC}}}\right)$$

where the $E_{\text{MAX}}$ denotes the maximum of E-field intensity expressed in V/m and retrieved from the LINET lightning database, the $E_{\text{ADC}}$ is the maximum/peak of E-field change for the same IC or CG lightning stroke that is recorded by the Rzeszow station and is given by the relevant ADC bit unit, $c_{\text{RS}}$ is the relevant return stroke speed and is assumed to be $1.3 \times 10^8$ m/s, $\mu_0$ is the magnetic permittivity of vacuum and equal to $4\pi \times 10^{-7}$ H/m, $I$ is the peak of lightning current reported in the LINET lightning database, $R$ is the horizontal distance to the considered CG lightning strike point from the Rzeszow station expressed in meters.

We have used the physical sign convention for all E-field changes presented in Figs. 2-5.

The exemplary PSD analysis of one of the numerous cases of IC lightning incidents that were successfully recorded by the Rzeszow station during thunderstorm season in 2014 is given in [Fig.2]. The obtained E-field signature of this discharge event is shown in details in [Fig.2e]. Here we can notice that the considered IC discharge was preceded by the remarkable sequence of some preliminary E-field breakdown pulses. Such great pulse burst initiates the following main stage of this IC flash. The time interval from this burst to the first recorded stroke of IC flash is 4.5 ms and its duration is 1 ms. There are several much smaller pulse bursts being seen and which are following the biggest E-field jump during the whole PB phase. The average time span between these pulses is about 100 µs. The polarity of E-field PB pulses was mainly positive and is opposite as compared to the polarity of the following main stage of the considered IC discharge. Such polarity change is the characteristic feature of all IC events recorded by the Rzeszow station. The structure of the PSD spectrogram of the PB stage of IC discharge is similar to this one obtained for the typical negative CG flash [6,7]. The spectral stripe of the PB stage of IC lightning is to some extent very heterogeneous.

![Figure 2](image-url)
There are a lot of local minimums and maximums in the considered frequency range. Moreover, the intensity/power of such PB stripes is decreasing with their increasing frequency. On the other hand, the additional PSD simulation done for the case of 25 MHz sampled E-field signature given in [Figs.2f-g] has shown that the dominant signal power is obtained for frequency of 4 MHz. It may be only the result of the used E-field antenna, for which the 3 dB cutoff frequency is equal 3 MHz.

The next example of the PB stage connected to another IC lightning discharge is presented in Fig.3. In this case the PB pulses are superimposed on a hook-like shape of the slower E-field signature. The simultaneous LINET lightning detection data reported for this IC flash have confirmed that the considered IC lightning activity has been localized not far from another CG flash. It is interesting that these initial IC lightning pulses are mainly superimposed on the rising slope of a big discharge E-field change with positive polarity. We can distinguish three separate E-field pulse bursts during the time development of the considered IC flash. The duration of these IC pulse bursts is about 5 ms and they are separated by 1 to 5 ms. There is one single NBP incident clearly seen in the middle of Fig.3g and that can be recognized as a different IC lightning activity connected to a compact intracloud discharge event [1], and involved in initiation of the new third IC pulse burst [see once more in Fig.3g]. The PSD spectrogram of the considered IC discharge is presented in Fig.3f. Here the distinct and separated sequences of spectral lines are well visible in the frequency range from 8 MHz to 9 MHz despite of the limited frequency response of the used E-field antenna. The spectral structure of the PB stage for this IC lightning is similar to that one given in Fig.2. The only one difference between them is that for the second case shown in Fig.3 the particular spectral PB stripe has the much wider time window than for this IC lightning case presented in Fig.2. It is caused by the longer time duration of the PB pulse bursts for the first considered IC flash than for the second one. The subsequent STFT analysis applied to the second IC discharge and given in [Fig3.a-d] has shown a great influence of the used STFT parameters on its spectrogram display. The wrong choice of such parameters may result in bad type identification of the particular components/stages of the considered IC flash.

The following two examples of the PSD spectrogram analysis of IC discharge incidents are based on E-field recordings performed in the Warsaw station with the frequency sampling of 50 kHz.

The long lasted sequence of the K-type E-field changes recorded during one single IC flash is presented in Fig.4. There are 43 of such IC lightning spikes/strokes occurring in the time interval of 330 ms. Thus we have obtained 7.7 ms as the average time interval between the consecutive K-pulses and giving the mean time duration of numerous J-changes associated with this IC lightning. It is typical value for the IC discharge incidents reported in literature [1]. The negative polarity of all ΔE-field changes linked to K-changes can indicated that the distance to this IC flash source was not so far from the measuring site [1]. There is a relatively slow E-field increase just after two close in time strong K-changes occurring.
at the end of the considered IC discharge and which is associated with the final long F-change. During this final stage of the whole IC discharge a remnant of the previous positively charged leader of the last K-change can supply some fresh amount of negative electric charge to the IC flash origin source from the more distant negatively charged thundercloud layer. Such late stage of the considered IC flash lasted about 70 ms. The PSD spectrogram of the K-type E-field changes recorded during the reported IC is presented in Fig.4a. It is obtained from the primary E-field record given in Fig.4b that is sampled with the sampling frequency of 50 kS/s. Here we can see the spectral line base with strong intensity/power and numerous small spectral stripes confirming the absence of higher frequency band for that IC flash components. This feature may be useful for the future elaboration of a new spectral identification procedure of such K-changes associated with IC flash and their differentiation from similar RS changes in CG flash.

The example of the positive multiple peaked NBP episode that occurred during IC lightning discharge incident and which has been selected from its E-field recordings carried out in the Warsaw station is shown in Fig.5b together with the relevant time extension given in Fig.5d. Such NBP events was easy to distinguish due to its high E-field amplitude and very narrow shape in compare to rest of other E-field pulses recorded during the considered IC flash. Similar NBP incidents recorded during this IC lightning were previously reported by Rakov [1]. The time width of the presented NBP episode was about 2 ms, but it’s the fastest E-field front lasted only 200 µs. It is worth to note that the observed change in polarity of some IC lightning pulses indicated in Fig.5b at the time moment of 33.98 s and 34.07 s, respectively, can confirm that during this IC lightning discharge process some parts/pockets of electric charge with different polarity and located closely to each other in thundercloud were involved. The PSD spectrogram of the selected NBP episode is shown in Fig.5c. It is similar to these PSD spectrogram obtained for the RS stages of CG flashes and

Figure 5. The PSD spectrogram of the multiple peak NBP incident superimposed on the IC lightning E-field signature recorded in the Warsaw station on July 19, 2015 at 18:15:33.583525 (UTC). The used STFT parameters and the sampling frequency are the same as for Fig.4. Note that the greatest peak and intensity of the PSD spectral stripe which is corresponding to the considered NBP incident can be easily distinguished from other numerous components/pulses of this IC discharge event. Several similar NBP incidents, not presented here, were observed during this IC flash. The only one difference between them is their different PSD amplitude/intensity that is obtained as greater one for the NBP episode than for the RS lightning incident. It is result of higher E-field amplitude and smaller time duration of E-field signatures connected to NBP incidents as compared to these ones recorded during RS changes.

IV. CONCLUSION

This paper was intended for showing usefulness of spectral analysis for identification of different components of IC lightning. The presented PSD analysis was performed for several different IC lightning components and was focused on studying of their spectrograms obtained in the early/initial stage of IC discharge development. The obtained results from two different measuring sites in Poland have shown a good agreement with these previously reported in the literature. On the other hand, such spectral analysis was proved to be very useful for conducting the adequate identification of variety types E-field signatures corresponding to the particular IC lightning incidents as the preliminary breakdown stages, K- and J-changes, or even the narrow bipolar pulse episodes. It
seems also to be a useful tool for the elaboration of a new and more effective discrimination computer procedures needed for IC and CG flash detections and that are still requested by some updating procedures of the global and regional lightning location systems operating continuously on the whole Earth globe. Moreover, the PSD analysis is able to deliver a lot of information about the frequency content of any lightning E-field changes. It is also a very efficient and promise way to obtain proper identification of different types of lightning strokes together with their time development. There are a lot of lightning channel engineering models used in lightning protection techniques which are referred to the frequency domain analysis of lightning E-field signatures. Therefore better knowledge about the PSD spectrogram of different lightning discharges and their precursor will give better understanding of the variety of physical processes involved in these unpredicted yet lightning phenomena. Knowing that IC lightning plays a role in the formation and intensity of many kinds of extreme weather, we should pay more attention on farther studying its E-field precursor and the relevant PSD spectrograms.

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