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Recent Observations of Lightning Strikes to Wind Turbines and Railway Overhead Lines

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SUMMARY

This paper presents recent analyses of lightning observations in the Austrian Alps gathered by Graz University of Technology in cooperation with the Austrian Lightning Detection and Information System (ALDIS). The project "Lightning Observation in the Alps – LiOn" was initiated in 2017 to record ground truth data of atmospheric discharges in the Alpine region. Atmospheric discharges were observed at 21 different measurement locations using a Video and Field Recording System (VFRS). This system consists of a high speed video camera (2000 frames per second) and a flat plate antenna to measure the electric field. Both, the camera and the electric field measurement system, are synchronized with GPS time and can therefore be correlated with Lightning Location System (LLS) data.
Two special cases have been recorded in the pre-alpine area during warm season thunderstorms of 2018. The first case shows a flash consisting of four downward strikes to two different wind turbines. The two wind turbines are part of a wind farm comprised 21 generators situated on a mountain ridge with a height of about 1450 m above sea level. The protocol data of the wind farm operator were correlated to VFRS and LLS data. The second case shows a flash consisting of three strokes, which hit a railway overhead line. The strokes caused flashovers on the insulators of three towers. The railway track is situated in build-up terrain; no train was on the section of the track in the moment of the lightning strike. The network protocol data of the Austrian railway operator and the related digital fault record of the installed distance protection relay was again correlated to VFRS and LLS data.
Results of this report shall contribute to a better understanding of lightning processes in general and in the Alpine region in particular.

KEYWORDS

Cloud-to-Ground Lightning; Wind Turbine; Railway Overhead Line; Ground Truth Data; Lightning Location System;

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1. INTRODUCTION

During warm season thunderstorms ground truth data measurements of cloud-to-ground (CG) discharges have been carried out by Graz University of Technology in cooperation with ALDIS. This research runs under the project name "Lightning Observation in the Alps – LiOn" from 2017 on. For the present analysis ground truth data of measurements of 2018, recorded with the VFRS, have been used. The observation of thunderstorms on 21 different spots all over Austria is one goal of the project. Such a research project can only be conducted if precise weather information and forecasts are available for the spots. In particular, the support of the national meteorological service ZAMG contributed decisively to its success. For detailed information see [1 – 9].
The investigated CG discharges can directly impact existing infrastructures and beings. Parameters for technical applications and characteristic values for future work in lightning protection can be derived from the recorded data sets. The research in this project therefore represents a contribution to a better understanding of the physical processes of CG discharges in continental and mountainous regions of Austria during the main storm period from May to August.
During the measurement campaign of 2018 two flashes, one that directly hit two wind turbines (case 1) and another one, which hit a railway overhead line (case 2), have been recorded.
The strokes of case 1 can be clearly identified as downward strokes. As described in [10] downward lightning to high buildings, such as wind turbines, are more likely during deep convective situations (e.g. warm season thunderstorms) and, in addition, downward lightning strokes are the most frequent type of lightning in general. The exposure and the regional ground flash density are the two key parameters for the overall number of downward lightning strikes to a wind turbine (see again [10]).
A percentage of 30.4 % is given as an average outage rate caused by direct strikes to wind turbines in low mountain (pre-alpine) areas of Europe (statistics of late 1990, wind turbines today has doubled total height; see [11]).
The strokes of case 2 can be clearly identified as downward strokes too. For lightning strikes to overhead lines in general and railway overhead lines in specific the same rules apply as described for wind turbines. Outages of overhead lines could be caused by direct strikes to a phase wire (shielding failure, in case of an installed overhead ground wire), a back flashover after a strike to the tower or the overhead ground wire and a flashover in consequence of a nearby stroke to ground or structures (see [12]). The ground flash density and lightning exposure of Austrian overhead transmission lines have been analyzed in [13]. A correlation of lightning discharges and transient measurements in the Austrian high voltage transmission system have been shown in [14]. In [15] a similar case of a strike to a railway overhead line has been analyzed for Brazil.
Data of the recorded cases, correlated LLS data and additional data provided by the system operators will be discussed in the next chapters.

2. MEASUREMENT SETUP

2.1 Video and Field Recording System

The VFRS is used to record ground truth data of atmospheric discharges in Austria. With this system on-site observations at selected places, where thunderstorms are predicted for that day, are possible. Such a transportable system allows observing thunderstorms at variable locations. For naturally occurring CG flashes, electric field and video data can be recorded in the observed area [1 - 3]. The system consists of two main components: a high speed camera and an electric field measurement system, which records the transient electric field. The synchronization of both components to GPS time provides the proper conjunction and comparability of the data of each atmospheric discharge. The electric field measurement system is described in [1]. During the measurements a video frame rate of 2000 frames per second, a 14-bit image depth and a resolution of 1248 x 400 pixels was most appropriate for the camera used (see [2, 3]). Each VFRS measurement data is correlated with the ALDIS LLS data by using the GPS time.

2.2 Lightning Location System

ALDIS operates a sensor network of eight lightning detection sensors in Austria. In 2001 ALDIS became one of the processing centers of EUCLID and is therefore processing the data of currently 166 sensors distributed all over Europe. The ongoing comparison of detected strokes with ground truth data, as recorded by VFRS or at the instrumented Gaisberg Tower, helps to determine the performance of the system regarding location accuracy, detection efficiency and peak current detection. Due to continuous adaptation and improvement of the system, the median location accuracy is in the range of 100 m in the center of the network. Analyses of performance parameters such as location accuracy, multiplicity and peak current distribution are shown in [1 - 4, 6 - 9].

2.3 System Protection Relays

The protocol of the wind farm operator, with information about the earth-fault detection relay data, was analyzed for case 1. Data of a distance protection relay, which is installed in the closest substation to the strike point, was analyzed for case 2. Digital protection relays are able to record a fault record. The record consists of analog and digital inputs that can be wired and calibrated by each operator. Both systems are synchronized to server time.

3. DATA

3.1 General Information

The measurements were performed in July and August 2018. These two months are part of the main warm thunderstorm season for the investigated area (see [7] and [16]). In total 217 negative CG flashes and 693 negative CG strokes were recorded during 14 days in Austria in 2018. Every dataset was analyzed manually to determine each individual stroke per ground strike point (GSP), visible in the video record.

3.2 Case 1: Lightning Strike to two Wind Turbines

The wind turbines of case 1 are parts of a wind farm comprised 21 generators situated on a mountain ridge with a height of about 1450 m above sea level. Each of these three-bladed wind turbines has a maximum height of around 120 m and a nominal power of 2.6 kW. The wind farm is shown in Fig. 1. The recorded flash consists of four strokes. Three strokes hit one turbine (first stroke one (FI1) and two subsequent strokes (SU1) within the same channel) and the forth stroke (FI2) followed a new channel and hit a second wind turbine. A downward stepped leader is visible in the video before the first return stroke. Also for the fourth stroke a downward stepping process is visible. All four strokes have been detected by the LLS. A correlation of the VFRS data and the LLS data is possible because of the used GPS time. The installed relays in each wind turbine are synchronized to server time (time resolution seconds) but no other event was recorded for the wind farm on that day.

Figure 1: Wind farm on a pre-alpine mountain ridge (ca. 1450 m a.s.l.); Stroked wind turbines 1 and 2 highlighted; © Google Maps

3.3 Case 2: Lightning Strike to a Railway Overhead Line

The railway overhead line in the analyzed section consists of a phase wire, mounted on top of concrete towers, and the feeder in the height of the pantograph. The Austrian railway system is operated as a single phase system and the railway track is used as return conductor. The line, operating on a voltage level of 15 kV and a frequency of 16.66 Hz, is connected to two substations. Digital protection relays and inductive instrument transformers are installed in both substations. Fig. 2 shows a section of the analyzed track. No train was on the track section in the moment of the lightning strike.

The recorded flash consists of three strokes, a first stroke (FI1), with a prior visible stepping process from cloud to ground, and two subsequent strokes (SU1). The digital protection relays recorded a fault record for this case. A correlation of the VFRS data and the LLS data is possible because of the used GPS time. The installed relays in the substation are synchronized to server time (time resolution ms) but no other event was recorded for this day.

Figure 2: Railway overhead track in the analyzed section; Tower structure highlighted; © Markus Hipfl, bahnbilder.warumdenn.net

4. RESULTS

4.1 Case 1: Lightning Strikes to two Wind Turbines

For case one, a correlation of VFRS and LLS data with the network fault protocol of the wind park operator was possible. Six frames of the high speed video of this case are shown in Fig. 3. The negative flash, including all four strokes, was correctly detected by the LLS. The strikes to the first wind turbine triggered the installed earth-fault detection relay. Stroke one to three had calculated currents in the range of -6 kA to -23 kA. The strike points of the three strokes were located in a distance range of 65 to 140 m to the first turbine (first stroke one (FI1) and two subsequent strokes (SU1) within the same channel). The GSP of stroke four (first stroke two (FI2); new GSP) was detected by the LLS in a distance of 775 m to the second wind turbine. This stroke had a peak current of -3 kA and did not trigger the earth-fault detection relay of the turbine. The high speed video shows a direct strike of stroke FI2 to the second wind turbine followed by a continuing current with a duration of 117 ms. The locations of the wind turbines, LLS detections and 50 % confidence ellipses of the strokes are shown in Fig. 4. The data of the LLS and the distances of the calculated locations are given in Table 1.

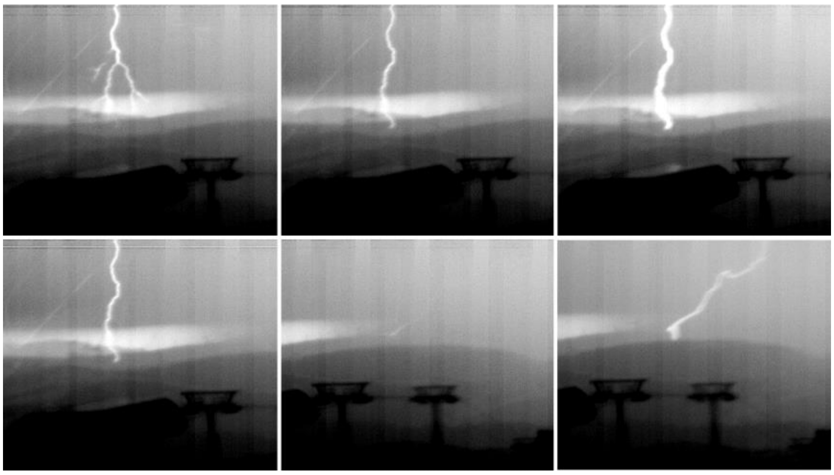

Figure 3: Stepped leader of FI1, first return stroke (FI1), subsequent strokes 2 and 3 (SU1), stepped leader of FI2 and second return stroke (FI2) from top left to bottom right; © LiOn IHS TU Graz 2019

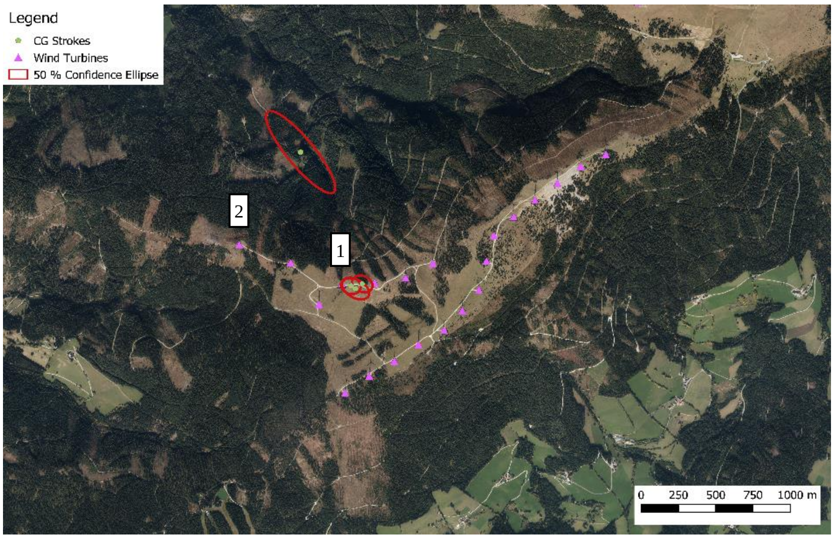

Figure 4: Locations of the wind turbines, LLS detections and 50 % confidence ellipses of the four strokes; Strokes 1 to 3 hit wind turbine 1, stroke 4 hit wind turbine 2; ESRI satellite map in the background

Table 1: LLS data for case 1 with distance to wind turbine 1 and 2 in m (Peak current in kA, sn = stroke number, nbdf = sensor detections, nbdfit = sensors data with succifient quality, maxis = major axis, ki2 = quality criteria, LDA = type of stroke, FIx = first stroke to GSP x, SUx = subsequent stroke to GSP x)

Latitude	Longitude	Peak Current	sn	nbdf	nbdfit	maxis	ki2	LDA	Distance
47.5316	15.7050	-23.2	1	56	19	0.1	0.3	FI1	64
47.5314	15.7054	-6.3	2	9	8	0.1	0.6	SU1	99
47.5317	15.7060	-9.9	3	15	12	0.1	0.5	SU1	137
47.5403	15.7009	-2.9	4	5	3	0.4	0.2	FI2	775

4.2 Case 2: Lightning Strike to a Railway Overhead Line

For case two, a correlation of VFRS and LLS data with distance protection relay fault records of the Austrian railway operator was possible. Six frames of the high speed video of this case are shown in Fig. 5. The negative flash, including all three strokes, was correctly detected by the LLS. The start time of the short circuit in the digital fault record correlates with the LLS time of the first stroke (timestamp accuracy of distance protection relay in ms). Stroke one to three had a calculated current of -4 kA to -10 kA. All three strokes hit the same tower (same GSP visible in the video). These three strokes were located in a distance range of 81 to 1424 m from this tower. The data of the LLS and the distance of the calculated location to the tower is shown in Table 2. The first stroke caused a flashover, visible in the video for 79 ms, on the affected tower and on two other towers. For this reason, a direct impact on the overhead line can be assumed. After 46 ms the line was tripped and after 123 ms the whole fault handling was closed by the distance protection relay. No transient signal changes, caused by atmospheric discharges, were detected in the digital fault records because of the low sampling rate of the protection relay (20 samples per period) and the used inductive instrument transformers. They are installed to generate an image of the 16.66 Hz component for measurement and protection purposes. The locations of the railway track, LLS detections and 50 % confidence ellipses of the strokes are shown in Fig. 6. The data of the LLS and the distances of the calculated locations are given in Table 2.

Figure 5: Stepped leader, first return stroke (FI1), flashover on two towers, subsequent stroke 2 (SU1), flashover on three towers and subsequent stroke 3 (SU1) from top left to bottom right; © LiOn IHS TU Graz 2019

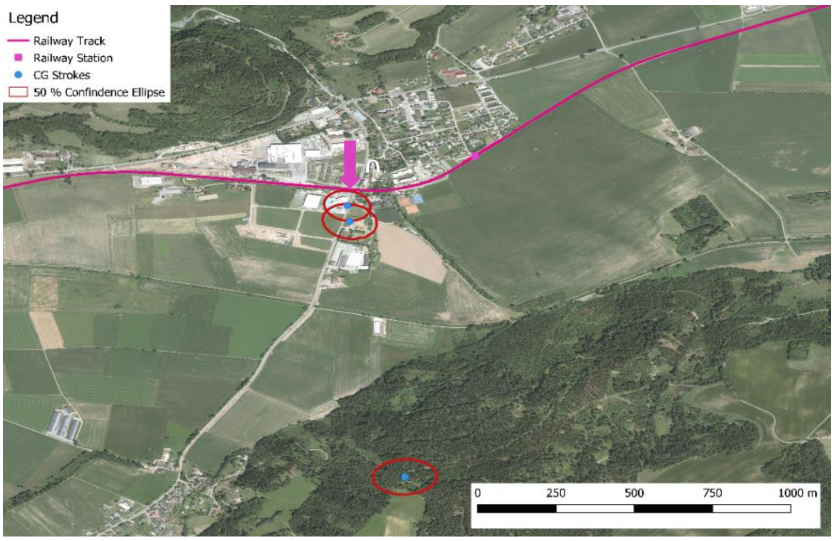

Figure 6: Railway track, locations of the LLS detections and 50 % confidence ellipses of the three strokes; tower position highlighted, all strokes hit the same tower; ESRI satellite map in the background

Table 2: LLS data for case 2 with distance to the railway transmission line in m (Peak current in kA, sn = stroke number, nbdf = sensor detections, nbdfit = sensors data with succifient quality, maxis = major axis, ki2 = quality criteria, LDA = type of stroke, FIx = first stroke to GSP x, SUx = subsequent stroke to GSP x)

Latitude	Longitude	Peak Current	sn	nbdf	nbdfit	maxis	ki2	LDA	Distance
46.7217	14.2894	-10.2	1	16	13	0.1	1.6	FI1	1424
46.7330	14.2871	-3.9	2	6	6	0.1	1.2	SU1	160
46.7337	14.2870	-5.5	3	10	10	0.1	1.0	SU1	81

5. DISCUSSION

The two analyzed cases show recent records of atmospheric discharges in the Austrian Alpine region. Ground truth measurements give an insight to lightning strikes to infrastructure in the observed area, both for buildings on mountainous and flat terrain. The dataset of the Video and Field Recording System (VFRS) measurements and corresponding LLS data were synchronized to GPS-time. This is a key factor for such correlations.

System protection and detection relays are synchronized to server time for both cases. A fault within the same second as the VFRS was detected by the detection relay for case 1 and within the same ms by the protection relay for case 2. In addition no other event triggered the relays for that day. This made a precise correlation to VFRS and LLS data possible.

For case 1, the lightning strike to two wind turbines, two downward stepped leaders are visible in the video for stroke 1 and 4. Three strokes followed the first channel to the first wind turbine (first GSP). It was not visible in the video if the strokes hit the lightning diverter on the blade tip, the lightning receptor, the blade structure or the tower top (limitations of the video quality due to heavy rain and hail). One of the first three strokes triggered the earth-fault detection relay. Because of the detected peak current of about -23 kA for the first stroke (FI1), it is most likely that this stroke already triggered the earth-fault detection relay. The high speed video shows a direct strike to the second wind turbine (second GSP) followed by a continuing current with a duration of 117 ms for stroke 4 (FI2).

The deviation of 775 m of the calculated strike point for FI2 to wind turbine 2 is caused by poor LLS detections. FI2 was detected by five LLS sensors and the data of three sensors was processed for the location calculation. The analysis of the raw data of the sensor signals showed a signal shape for FI2 with a larger width and two field peaks (difficulty of defining the correct start time of the event leads to location inaccuracy). The relatively low stroke peak current of FI2 (-2.9 kA) and its inclined leader makes a correct location calculation of this stroke more difficult too. LLS location calculations for the other strokes show strike points in a distance of 64 m to 137 m from the first wind turbine. This value is comparable to values of the median location accuracy of the ALDIS LLS (see [8]). The operator of the wind farm reported no lasting damage of the wind turbines, which were hit by lightning.

For case 2, the lightning strike to a railway overhead line, again a downward stepped leader is visible in the video. All three strokes followed the same channel to the same GSP. The railway overhead line is not directly visible in the video but a flashover on the insulator of the tower at the GSP and two towers in the surrounding are visible. For that reason a direct strike of the overhead line is most likely. The flashover was visible in the video for 79 ms, on the affected tower and on two other towers. The analysis of the digital fault record of the distance protection relay shows that the line was tripped after 46 ms. After 123 ms the whole fault handling was closed by the distance protection relay. The difference of 33 ms between the tripping time of the line and expired flashover in the video could be caused by a mechanical breaker closing response time and an eventual time shift between the tripping times of the two substations. The installed distance protection relay operates with a sampling rate of 20 samples per period and the used inductive instrument transformer is built to generate an image of the sinusoidal 16.66 Hz signal, for measurement and protection purposes. For that reason no transient signal changes, caused by atmospheric discharges, can be detected in the digital fault records. To detect such transient

signals on the line a resistive-capacitive voltage divider and a transient measurement system is needed (see [14]).
The large deviation of the calculated strike point of stroke 1 (FI1) to the tower (1424 m) is again caused by poor LLS detections. The analysis of the raw data of the sensor signals for FI1 showed a signal shape with a larger width and two field peaks too. This causes the same problems as described for case 1. Location calculations for the other two strokes show strike points in a distance of 81 m to 160 m to the tower of the overhead line. This value is comparable to values of the median location accuracy of the ALDIS LLS (see [8]). The Austrian railway operator reported no lasting damage along the transmission line, which could be attributed to this lightning strike.
To correlate lightning strikes, detected by the VFRS and the LLS, with fault records in the transmission system or strikes to wind turbines, a time synchronization to GPS-time has to be implemented in these systems in the future.

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