VI Russian Conference on Lightning Protection

17-19 April, 2018, Saint Petersburg

I. Uglešić, B. Franc, N. Stipetić

Faculty of Electrical Engineering and Computing

University of Zagreb, Croatia

Lightning stroke measurements, data verification and application in power systems

SUMMARY

The paper presents the lightning stroke measurements performed by different measurement systems. First, the lightning activity monitoring system at Lovćen tower is presented. The mountain Lovćen is located close to the sea coast, in the area with high lightning flash density. This makes the measurement station unique compared to other lightning activity monitoring systems in Europe. Furthermore, the application of lightning data in transmission system control is presented as well as new problems related to wind turbine installations. Blade damage experience in one wind power plant led to lightning event counter installation in each blade at all wind turbines which enabled the collection of information on direct lightning strokes to wind turbine blades. The data collected by the lightning current measurements at Lovćen tower and by lightning event counters in the wind turbine blades enable the evaluation of the lightning location system data.

KEYWORDS

lightning location system, direct lightning strokes, lightning stroke measurement, correlation process, lightning flash density, wind turbine

1. Introduction

Lightning detection and mapping systems are broadly used today by operators of systems whose equipment can easily be damaged because of its exposure to lightning strokes. The lightning data from lightning location systems can minimize the harmful effects of lightning by providing early warnings of such hazards [1]. To design the effective lightning protection, one should be familiar with parameters of lighting currents that are analyzed based on direct lightning current measurements. The direct lightning current measurement at mountain Lovćen is presented in [2]. Different example of the lightning recorded at this tower is compared to the lightning registered by the lightning location system (LLS) in this paper.

The LLS in Croatia operates since 2009, as part of LINET network which contains more than 130 identical sensors in Europe. The Croatian LLS records all lightning events in Croatian territory and neighboring countries. The lightning correlation service was developed to serve as a utility function in transmission system operator power system control. Based on time and spatial analysis, its duty is to identify the events in the transmission network that were caused by lightning. By correlating the relay protection data and the LLS data, the verification of registered lightning strokes could be achieved. Also, by analyzing the lightning data and correlated data advanced planning and improved control of the power system is possible.

Recently, as the installed wind power capacity started to rise, the lightning data was proven to be valuable for assessing the wind turbine exposure to lightning strokes. Problems related to lightning and wind turbines incidence are reported all over the world, but site-specific parameters such as relatively high isokeraunic levels combined with high soil resistivity contribute to protection design and dimensioning challenges. Recent blade damages in one WPP lead to lightning event counter installation in each wind turbine blade. The lightning current sensor detects lightning strokes to the wind turbine blades and logs the peak current amplitudes and time of strokes. The available data from the lightning event counter enables the exact information on wind turbine exposure to direct lightning strokes and gives another possibility for verification of the LLS data.

2. Direct lightning current measurement at mountain Lovćen

Direct lightning current measurements are performed on the broadcasting tower Lovćen (mountain Lovćen, Montenegro). The mountain Lovćen is located close to the coast, which makes the measurement station unique compared to other lightning activity monitoring systems in Europe (Santis tower-Switzerland, Gaisberg tower-Austria, Peissenberg tower-Germany). Contrary to other towers, Lovćen area has significantly higher lightning stroke density and more measurements can be collected and analysed. The altitude of the mountain is 1749 m and the tower is 88 m high. According to the available LLS data (2009-2017), the lightning stroke density for the tower area is 1063 [strokes/km^2 year]. The number of registered lightning strokes and flashes within the alarm zone (2000 m) around the Lovćen tower is given in Table 1. Annual number of strokes varied from 508 strokes in 2015, to 3378 in 2012. It was noticed that there is more lightning activity in winter, especially in February.

Table 1. The LLS data - registered lightning activity for Lovćen tower area

LLS data 2009-2017 (last 9 years) 2 km radius around Lovćen tower			
Total lightning strokes	13122	IC lightning strokes	1721
CG lightning strokes	11401	No. of lightning flashes	4390
CG negative strokes	10637	No. of subsequent strokes	7011
CG positive strokes	764	Flash multiplicity factor	2.597

2.1. Monitoring system installation

The lightning monitoring system at Lovćen tower is a real-time remote monitoring system and it is fully automated. A current transformer is used for direct measurement of the lightning current shape. Additional three independent systems are integrated to confirm the direct current measurement: the IP camera, the electric field sensor and the transient recorder [2]. The Lovćen tower and the block diagram of the monitoring system are shown in Figure 1.

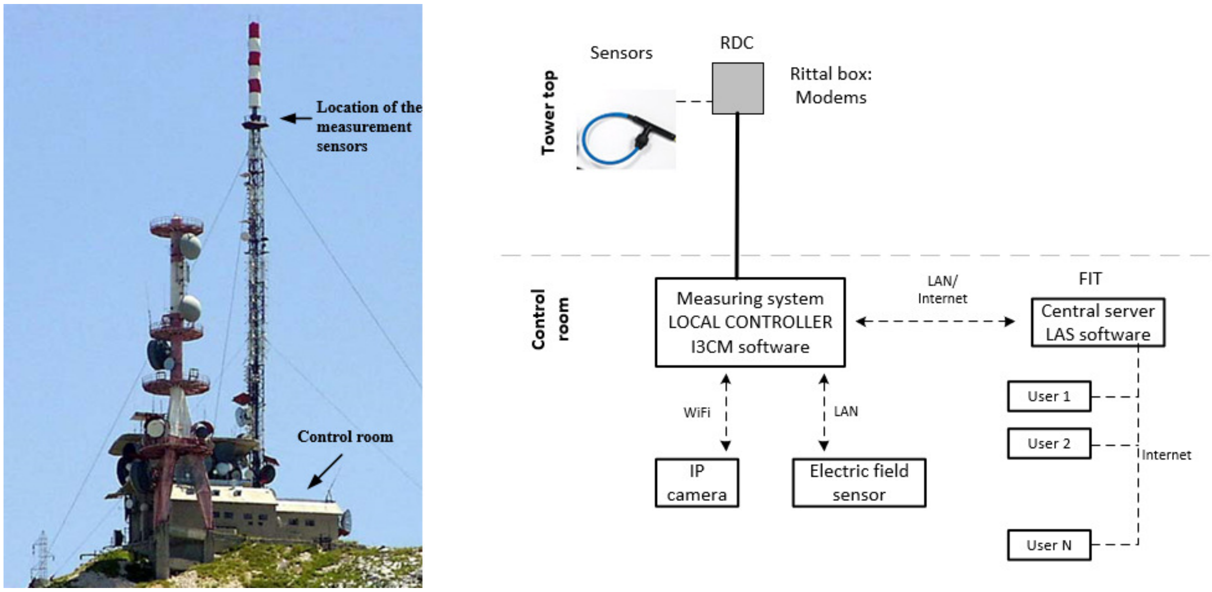


Figure 1. Lovćen tower and the block diagram of the monitoring system

The 500 kA impulse current transformer is connected to the monitoring system. The GPS synchronized IP camera registers lightning hitting the tower top. Electric field sensor is used to register electric field changes. The data provided from this sensor can be useful to find correlation between electric field peak and lightning current peak and compare it with the existing methods. The power quality monitoring equipment is used to find out which disturbances on distribution line that supply tower are produced by lightning. All data are transferred in real time by internet to the central server and stored into the integral information system. The application installed on central server displays broadcasting tower location on a map and enables the data for each recorded event: date, time and lightning current shape. Comparing the data recorded by all sensors, it is possible to get more accurate data about lightning event.

2.2. Measurements at Lovćen tower compared to LLS data

In order to compare the direct current measurements at Lovćen tower with recorded data by the LLS, a thunderstorm on 6th of March 2016 (Figure 2) was taken as a study example.

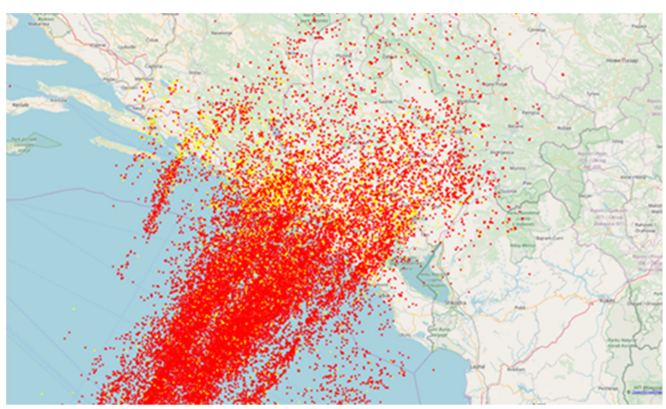


Figure 2. Lightning recorded by the LLS during the thunderstorm on 6th of March 2016

Both systems recorded the lightning that occurred around 16:09:13. Two measurements of the lightning current were recorded at Lovćen tower, as shown in Figure 3. The LLS registered one multiple-stroke lightning flash, with 18 strokes within the tower alarm zone (2000 m radius around the tower). A greater number of detected strokes can be explained by the larger detection area as well as the high sensitivity of the LLS. Figure 4 shows locations of 18 recorded strokes by the LLS.

Table 2 and Figure 5 present the comparison of the recorded data by both systems. One can note that timestamp of the measurements at Lovćen tower are the same for both measurements, because exact microseconds were not registered.

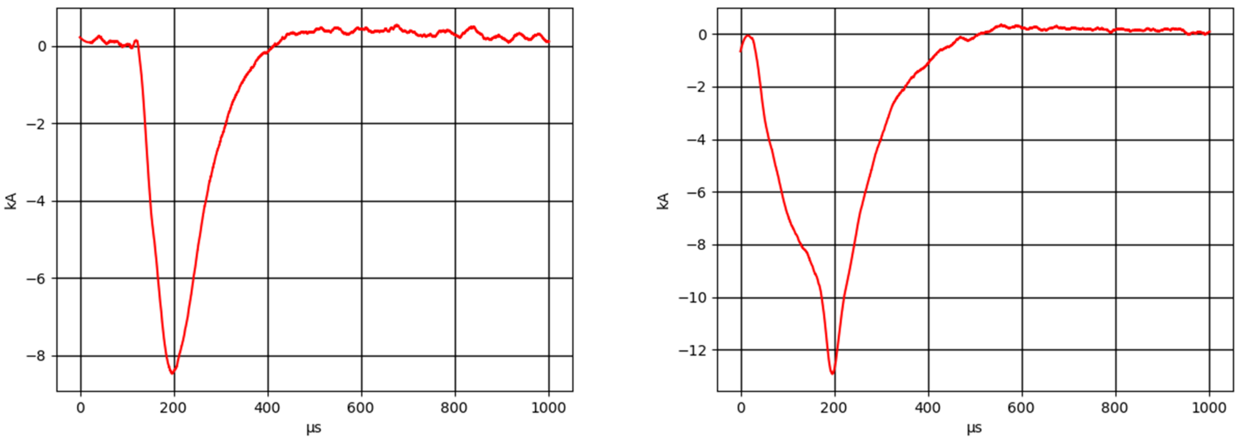


Figure 3. Lightning current shapes measured at Lovćen tower on 6th March 2016 at 16:09:13

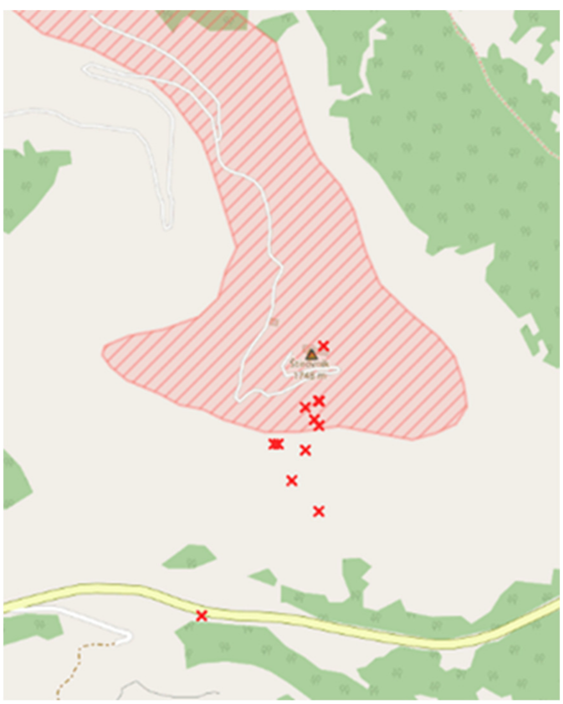


Figure 4. Locations of 18 strokes recorded by the LLS at Lovćen tower alarm zone on 6th of March 2016 at 16:09:13

Table 2. Comparison of recorded lightning strokes by direct measurement on the Lovćen tower and by the LLS

Direct measurement at Lovćen		**The LLS**	
Measurement timestamp	**I_{max} [kA]**	**LLS timestamp**	**I_{max} [kA]**
16:09:13,000	-8,586	16:09:12,786	-2,2
16:09:13,000	-13,145	16:09:12,797	-2,4
		16:09:12,803	-3,6
		16:09:12,808	-4,7
		16:09:12,816	-2,4
		16:09:12,824	-5,3
		16:09:12,831	-3,4
		16:09:12,843	-6,5
		16:09:12,852	-5,1
		16:09:12,864	-2,8
		16:09:12,865	-2,4
		16:09:12,866	-2,7
		16:09:12,910	3,7
		16:09:13,129	-5,3
		16:09:13,164	-11,5
		16:09:13,179	-3,7
		16:09:13,216	-7,9
		16:09:13,248	-4,5

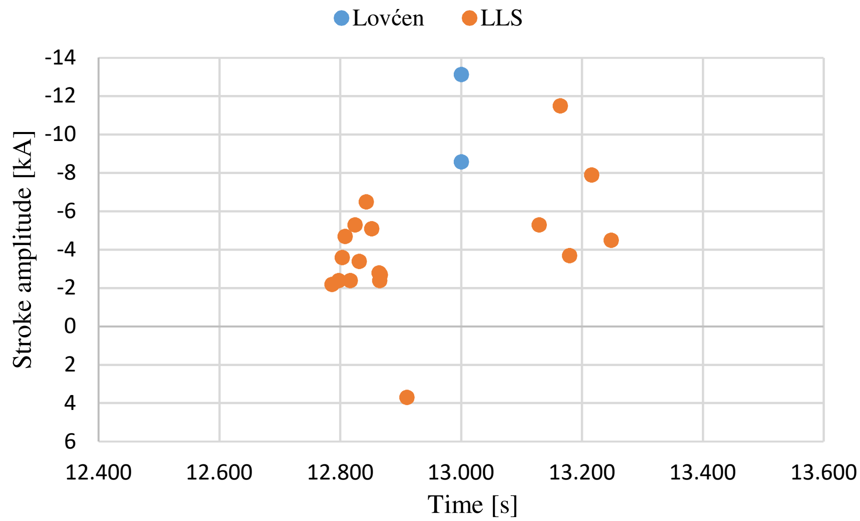


Figure 5. Comparison of detected strokes from both systems with respect to the time of the stroke occurrence and current amplitude

3. Lightning data application in power systems

The lightning location system in Croatia operates since 2009, as part of LINET network. For application in the power system, the LLS correlator was developed. Based on time and spatial analysis, the LLS correlator's duty is to identify the events in the transmission network that were caused by lightning. The LLS collator correlates three data sets – lightning data from LLS, chronological event list from SCADA and geographic data from GIS. As result it gives the correlated data - circuit breaker (CB) operations and lightning strokes that caused them. Results of the correlation are categorized based on nominal line voltage, peak lightning current amplitudes, polarity, geographical properties (location), time of lightning stroke and time of CB operation. The correlated data prove the time accuracy of the LLS and give the wide application possibilities in power systems.

3.1. Identifying the most exposed line segments to lightning strokes

The correlation process is done for transmission power lines (400, 220, 110 kV). The network scheme is adapted automatically in case of changes.

Each overhead line has an alarm zone along its length and all lightning strokes recorded within the alarm zone enter the correlation process. The radius of the alarm zone is calculated based on the total LLS error and it equals twice the location error, i.e. 1000 m (Figure 6), and it is possible to define the radius of alarm zone for each overhead line separately.

All detected strokes are grouped to flashes based on time and location criteria, hence both stroke and flash densities are available in the system. When identifying critical line segments, the stroke density maps are used. These high-resolution maps have determined stroke densities for each 1 km x 1 km area. The critical segments of overhead lines are those that contain high stroke densities in their alarm zones. To simplify the quantification of critical segments, the densities are divided into density classes with the step of 5 strokes/km^2 year. The frequency of each density class along the alarm zones of overhead lines is then observed and the most exposed segments to lightning strokes are defined. Figure 7 shows the most exposed transmission line to lightning strokes in 2016. Knowing where the most endangered line segments are enables implementation of precautionary measurements to avoid possible outages or damage.

Other algorithms that are being developed for application in the transmission network aim to identify close lightning strokes and CB auto-reclosures. Close lightning strokes might cause short-line faults that are difficult to interrupt and might decrease the CB interrupt capacity in the future. Therefore, identifying these CB operations will enable valuable information for CB maintenance and life-cycle strategy.

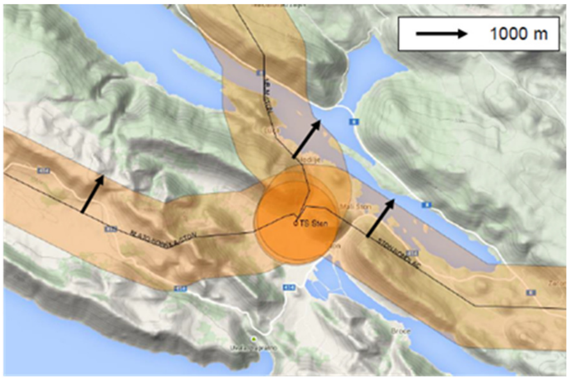


Figure 6. Alarm zone example

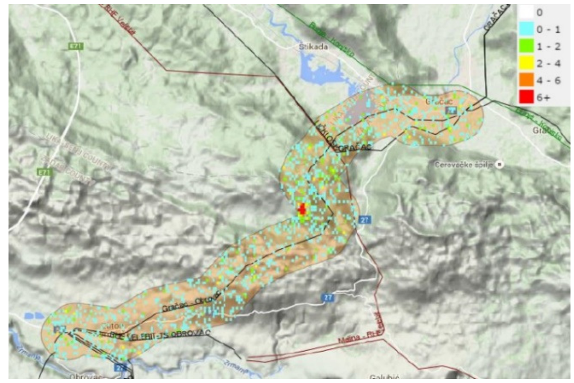


Figure 7. The most exposed transmission line to lightning strokes in 2016

3.2. Correlation results and statistics for 2016

Table 3 gives statistics on CB operations in 2016 with respect to the voltage level. Lightning causes more CB operations on lower voltage levels. Out of 11 918 signals regarding CB operations, 262 were correlated to lightning [3].

Table 3. Correlated CB operations by voltage levels

		400 kV	220 kV	110 kV	Total
2016	Total No. of CB operations	390	1 407	10 121	11 918
	No. of correlated CB operations	3	21	238	262

Figure 8 shows the number of correlated CB operations with respect to the current amplitudes that caused for each transmission voltage level. It can be noted that most of lightning induced CB operations occurred in 110 kV network and the mayority of the lightnig strokes that caused these CB operations had current amplitudes 10-20 kA. Significatelly less CB operation were registered in 220 kV network, and the lightning current amplitudes that cause CB operations are higher for 220 kV. In 400 kV network only three lightning induced CB operations occurred and the current amplitudes that cased them were significantly higher.

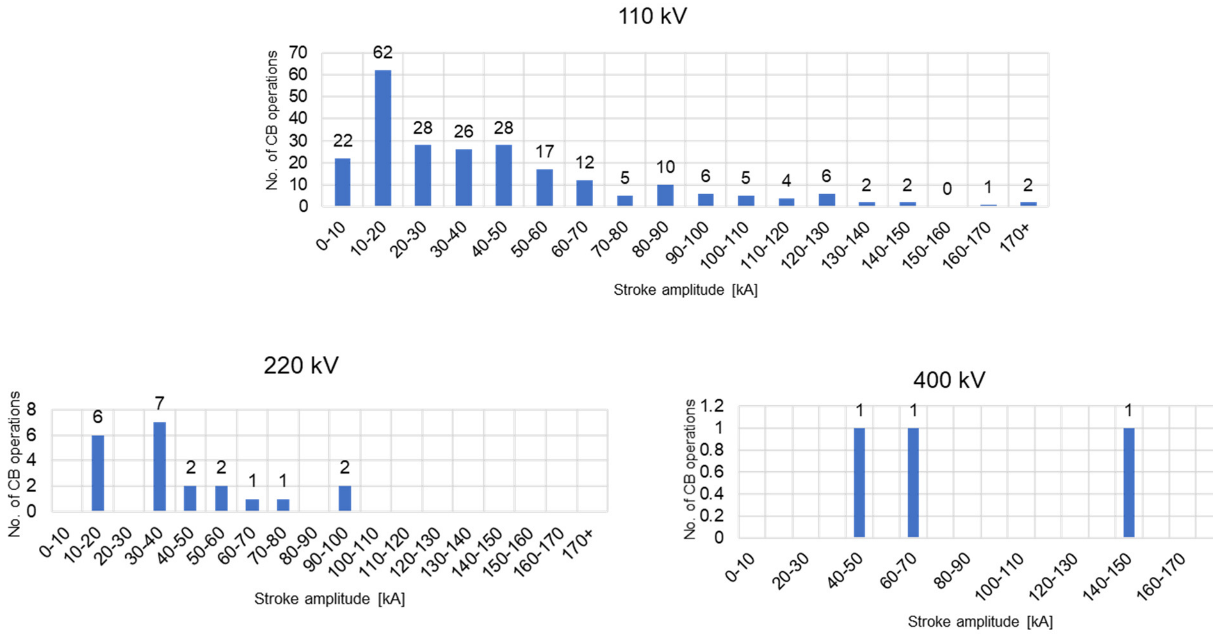


Figure 8. Number of correlated CB operations in 2016 with respect to the network voltage level and the lightning current amplitude that caused the CB operation

3.3. Application of lightning data in Wind Power Plants

Continuous monitoring and analysis of lightning data showed significant changes in lightning stroke densities at micro-locations where Wind Power Plants (WPPs) are installed. During the operation of WPPs, a number of damages and outages were reported due to lightning, despite the existing Lightning Protection Systems (LPS). These damages and production interruptions caused by lightning lead to installation of lightning counters in each blade of a WPP.

3.3.1. Case study - influence of the observed WPP installation to micro-location lightning activity

In order to achieve high productivity, inland wind turbines are preferably placed at high and windy locations that might already have relatively high lightning stroke densities. Since the wind turbines attract lightning strokes, one could assume the increase of lightning stroke density at the wind plant site and consequent increase in direct lightning strokes to wind turbines. The lighting stroke density change was observed for one WPP, which consists of 14 wind turbines and total installed capacity of 42 MW. Figure 9 shows the wind turbine positions.

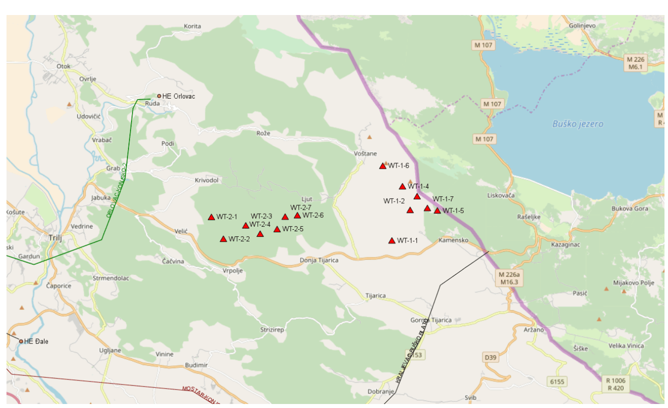


Figure 9. Locations of wind turbines in the observed WPP

Figure 10 shows the lightning stroke density map of the WPP location before and after the installation of wind turbines in 2013. The map on the left considers lightning data recorded 2009-2012 and the map on the right the data recorded 2013-2017. It should be noted that the detection sensitivity for LINET network was improved in 2016. More lightning strokes with smaller amplitudes started to be detected, and consequently there is a general increase in lightning stroke density. Nevertheless, the increase around wind turbine locations is significant, which proves the influence of wind turbines to the lightning activity. The most significant change is observed in the impact area of wind turbine WT1-4, where the stroke density after the wind turbine installation is 141.6 strokes/(km^{2}year), which is an increase of 5.25 times. Due to the geographic characteristic of the location, the relative height difference between the lowest and highest positioned wind turbine is 485 m and WT1-4 is, as expected, the most elevated wind turbine.

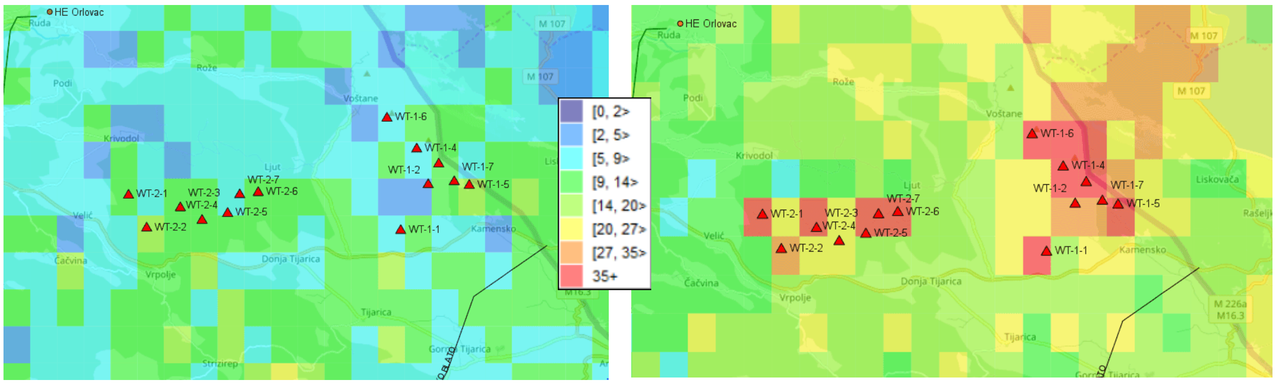


Figure 10. Lightning stroke density maps of the WPP location before (left) and after (right) the installation of wind turbines

Figure 11 shows number of cloud to ground strokes at the WPP area (sum of all alarm zones with 2000 m radius around each wind turbine) through years. The rise in number of strokes is obvious, but the polarity ratio remains approximately the same. The number of negative strokes in one year increased to 196 %, while the number of positive strokes to 161 %. Before the installation of wind turbines the positive to negative stroke ratio was 1:2.8, while after the installation it is 1:3.2.

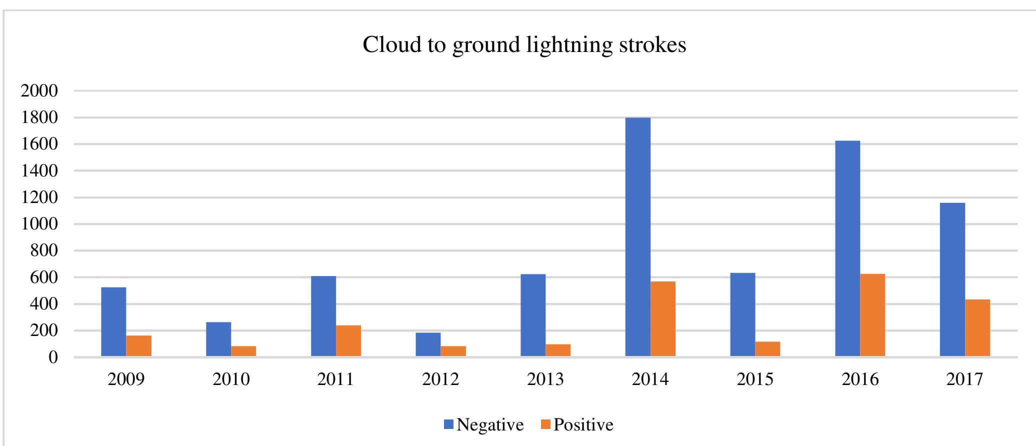
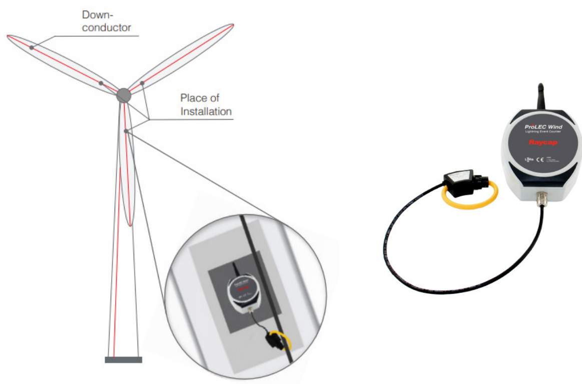


Figure 11. Comparison of number of positive and negative cloud-to-ground strokes through years 2009-2017

Additionally, a comparison of lightning current amplitudes before and after the wind turbine installations was done for both positive and negative strokes. The average and median amplitude values decreased, but the reason is the improved detection sensitivity within LINET network, which leads to more detections of strokes with smaller amplitudes and shifts the average and median amplitudes toward lower values [4][3].

3.3.1.1. Direct lightning strikes and lightning counter installation

Lightning tends to stroke tall objects capable of developing streamers or leaders, and sharp edges where the field enhancement is high. Hence, tall isolated wind turbines with sharp blade tips are very vulnerable structures from the Lightning Protection System (LPS) standpoint. The blades are the most exposed part of the turbine, exposed to direct strokes and the full electromagnetic and mechanical impact and energy content from the lightning current. Damage due to lightning is the most costly type of downtime event. Even if these events are not as frequent as others, the repair costs and lost revenues can strongly affect the operation costs, especially in high lightning-risk areas. Several studies have shown that at least 10 direct lightning strikes to a wind turbines in the multimegawatt range have to be expected every year [5]. In the observed WPP, the lightning event counters (Figure 12) were installed in each blade to monitor the number of direct strokes and to relate it to the LPS condition.



Threshold current (8/12 μs) [I_{tc}]	2 kA
Maximum Withstand Current (10/350 μs) [I_{mcw}]	250 kA
Current Measuring Range (10/350 μs) [I_{mcw}]	10 kA to 200 kA
Amplitude Measurement Error	10 kA to 200 kA: 10% ± 2 kA

Figure 12. Lightning current sensor installed in the blades of the observed WPP

The lightning event counter installed is a Rogowski coil with wireless data transmission. It collects information about frequency, time/date and amplitude of direct lightning strokes to each blade.

When direct strokes are observed in LLS, all strokes within equivalent attraction area $((3 \cdot \mathrm{H})^2\pi$, where H is the maximal height when the blade is aligned with the tower, i.e. the sum of the tower height and one blade length [6]) are considered direct. As it can be seen from Figure 13 on the right, the largest number of strokes are grouped around the most elevated wind turbine, WT1-4. However, one should have in mind that equivalent attraction areas of neighbouring wind turbines might overlap and that every recorded stroke has a system location error. Hence, the LLS data is relevant for the observation of stroke density and overall tendency of lightning activity at the WPP area, rather than for direct strokes.

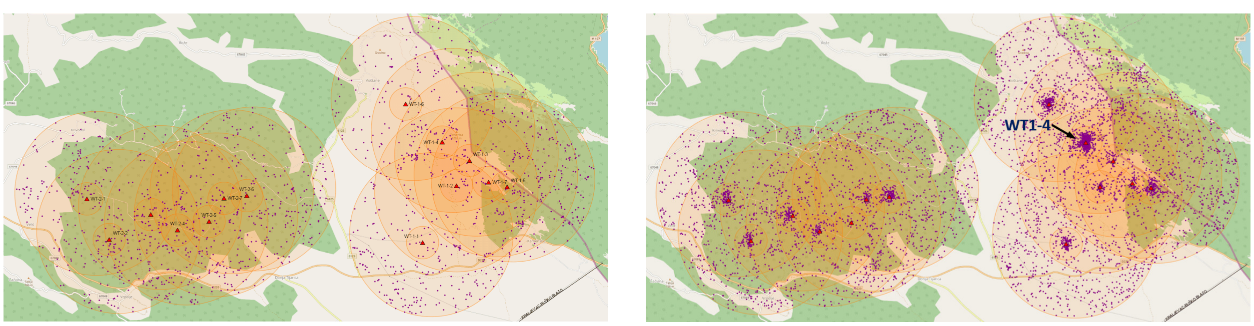


Figure 13. Map of the WPP location with visible strokes before (left) and after the wind turbines installation (right)

The more relevant data considering direct strokes should be the local measurement in the blades. The largest number of lightning strokes to one wind turbine in one year is 39, the largest number of direct strokes to a single blade was 18.

4. Conclusion

Direct real-time measurements record the shape and amplitude of the lightning currents. Comparison of a lightning event recorded at Lovćen tower and by the LLS showed a good congruence. However, the LLS recorded more strokes due to high system sensitivity and a wider area considered. Lightning locating systems are continuously improved and nowadays are a powerful tool in planning, protection and management of power systems. The lightning data was proven to be valuable for assessing the wind turbine exposure to lightning strokes. The lightning stroke density at a micro-location increases after the wind turbine installation which increases the risk of direct lightning strokes to wind turbine blades. The LLS data showed that stroke density increased, and the number of direct strokes is the greatest for the most elevated wind turbine. However, the wind turbine altitude, proximity to other wind turbines and the system location error will all affect the LLS data. When the wind turbines are close to each other, their equivalent attraction areas might overlap and the information on number of direct strokes should be taken with a reserve. The available data from the lightning event counters placed in each blade enables the exact information on wind turbine exposure to direct lightning strokes and gives another possibility for verification of the LLS data. However, their output and reliability should also be investigated prior to the comparison with the LLS data.

ACKNOWLEDGMENT

This work has been supported in part by the Croatian Science Foundation under the project "Development of advanced high voltage systems by application of new information and communication technologies" (DAHVAT).

5. Literature

[1] Vladimir A. Rakov and Martin A. Uman, *Lightning physics and effects*. 2003.

[2] A. Balota, D. Strujic, T. Sadovic, S. Sadovic, I. Uglesic, H.-D. Betz, "Lightning activity monitoring system on mountain Lovcen, Montenegro," in *International Colloquium on Lightning and Power Systems, Bologna 2016*.

[3] N. Stipetić, B. Franc, I. Uglešić, M. Mesić, I. Ivanković, "Improving lightning location system and advance control, maintenance and planning of transmission power system using lightning location system data," in *Internaational Colloquim on Lightning and Power Systems, Ljubljana 2017*.

[4] V. Milardić, B. Franc, I. Uglešić, B. Ivković, "Analysis of wind turbine blade damage due to lightning strokes," in *12th HRO CIGRE Session, Šibenik 2015.*

[5] DEHN, *Lightning Protection Guide, 3rd updated Edition*. 2014.

[6] "IEC 61400-24:2010 Wind turbine generator systems - Part 24: Lightning protection," 2010.