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LIGHTNING DATA UTILIZATION IN POWER SYSTEM CONTROL

SUMMARY

Lightning location systems (LLS) provide data on lightning activity such as lightning type, GPS location, exact time of the lightning stroke, lightning current amplitude, measurement error, etc. The proper application of LLS data using customized software support can be a powerful decision-making tool in the control, maintenance and development of power systems. The utilization of lightning data in power systems requires a customized software support with specific functionalities. Software functionalities include real time lightning activity visualization with alarm function; analysis, reports and historical lightning activity visualization; spatial correlation between lightning data and alarm zones around geographically represented power system's objects (power lines, power facilities, etc.); calculation of lightning statistics; generation of wide area lightning density maps, generation of high resolution lightning density maps inspecting alarm zones around the power lines; real time correlation between lightning activity and the power system protection equipment (distant protection relays), gathered through the SCADA system. In this paper, emphasis will be given to the application in correlation between faults and outages in the power network and lightning strokes. Today, many power companies monitor data related to circuit breaker operation or re-closing using various equipment. Such equipment allows online monitoring of circuit breakers and alarm statuses of equipment in substations.

Key words: circuit breaker operation, correlation, lightning location system, line faults, power system control

1 INTRODUCTION

Today, applications of lightning location systems (LLS) are well known in different industries and organizations such as insurance companies, air control, meteorological services, fire departments, military installations, telecommunication networks, network of broadcasting transmitters, oil and gas networks, dealers and distributors of explosives, petrochemical industry, etc.

The electricity companies and electrified railways became a customer of LLS relatively late and only after LLS were sufficient mature. In beginning LLS had numerous weaknesses, e.g. the inability to discern cloud to ground from inter cloud flashes, low detection efficiency, inaccuracies in determination of lightning location, detection of small stroke amplitudes, the inability to detect subsequent strokes, etc. All this prevented use of LLS in design control and management of overhead lines. In recent times the mentioned weaknesses are largely eliminated. Today, the modern LLS are increasingly used by power and distribution operators. Application in transmission and distribution networks and systems is mostly encountered in one or more of the following areas:

a) in correlation of outages and faults in network with lightning strokes;

b) in establishing, managing and monitoring of electric power system;

c) in giving a warning of coming lightning front;

d) in choosing the route of overhead lines and ways to protect them from lightning, [1-5].

In this paper, emphasis will be given on the application in area described as a) and b).

LLS data can be correlated with data of faults and outages in power network, which may contribute to power quality. Today, many electricity companies are following data related to circuit breaker operation or re-closing using various equipment for registration. Such equipment allows online monitoring of circuit breaker and alarm status of equipment in the substations. Comparison with LLS data shows that not all fault and outages during a thunderstorm are caused by lightning. A certain number of outages could be caused by intense winds during a thunderstorm causing two-phase or one-phase short circuit. The optimum method for determining the real number of circuit breaker tripping and re-closing, caused by lightning, is correlation of fault time and position from relay protection devices with LLS data. Relay pick-ups are the first signals upon registering a line event, thus are used for the time correlation with lightning data.

Frequent use of LLS data is made for identification of the circuit breaker tripping. Valuable information in decision making is the report, whether the lightning stroke has occurred just at the moment before of circuit breaker tripping and near the route of the line. Experienced operator can determine, using LLS data, whether the circuit breaker tripping is consequence of a permanent or transient failure. Such determination can be extremely useful in establishing the operation of a line, minimizing the required time and cost.

At the end of 2008, a lightning location system was constructed, covering a wide area of the Croatian territory as part of the LINET network. Six sensors have been installed in Croatia (Zagreb, Rijeka, Nin, Sinj, Dubrovnik, island Korčula). LINET is a modern lightning location system with a network of more than 125 sensors covering most of Europe. LINET sensors utilize VLF/LF frequency ranges and detect magnetic flux at the moment of an atmospheric discharge [6]. Figure 1 shows LINET sensors in Croatia and its neighboring countries [7].

Figure 1. LINET sensors in Croatia and its neighboring countries with monitored area

Lightning data gathered by lightning sensors are sent unprocessed through the Internet to the processing center, where data is processed and formatted. Formatted data is subsequently available for download to subscribed clients. Lightning data are taken from the processing center and stored in a local database. Data is available for the period beginning January 1, 2009. The monitored area is shown in Figure 1.

Lightning data include (Table I):

1. Time and date of lightning stroke (UTC);
2. GPS coordinates (2D);
3. Lightning current amplitude (0.1 kA resolution);
4. Lightning type (cloud-ground, inter-cloud);
5. Height (for inter-cloud lightning);
6. 2D statistical locating error (50% probability) [8].

Table I. Turbine regulation model parameters

GPS	TIMESTAMP	TYPE	HEIGHT	AMPLITUDE	ERROR
15.8932 45.7170	29.4.2009 18:57:05.595	CG	-	-15 kA	43 m
15.8920 45.7036	29.4.2009 19:07:32.771	CG	-	-5.2 kA	56 m
15.8508 45.7407	29.4.2009 18:50:47.143	CG	-	72.2 kA	51 m
15.8214 45.7566	29.4.2009 18:50:47.112	IC	3600 (m)	-5.5 kA	59 m
15.8647 45.7595	29.4.2009 19:07:01.673	IC	4100 (m)	4.7 kA	65 m
15.8117 45.7558	29.4.2009 18:49:09.457	IC	5900 (m)	-10.7 kA	87 m

2 2. UTILIZATION OF LIGHTNING LOCATION SYSTEMS IN POWER SYSTEMS

The utilization of lightning location systems in power systems is primarily enabled by one or more specific tasks:

1. Correlation between power outages and faults with lightning strokes;
2. Power system control and management;
3. Early lightning activity warning system;
4. Power system design (overhead line route planning and line protection).

2.1. CORRELATING POWER OUTAGES AND FAULTS WITH LIGHTNING STROKES

Lightning data can be correlated with data relevant to power outages and faults in the power system, which can improve the overall quality of power system monitoring. Modern power system operators monitor circuit breaker (CB) operation using various monitoring systems and acquire data through SCADA or similar data acquisition systems in real time. Circuit breaker operation can be correlated with lightning data, showing the number of CB operations, as well as the number of power outages caused by lightning strokes to the overhead lines [3].

2.2. CONTROL AND MANAGEMENT OF POWER SYSTEM

A common lightning location systems utilization concerns control and management of power systems, especially during periods when a dispatching centre is attempting to determine the cause of a circuit breaker operation. Information on a lightning stroke during a CB operation in proximity to an overhead line can be vital in determining the cause. The utilization of real time lightning tracking enables a skilled operator to determinate if a power outage was caused by a permanent fault or a transient fault due to a lightning stroke. Such a tool can be particularly useful in the restoration of regular operation, minimizing outage time and cost.

2.3. EARLY WARNING SYSTEM

System operators and engineers can use real time lightning tracking data to organize and prepare teams in areas where high lightning activity is approaching. Equally important is the ability to confirm the lightning front has completely passed the monitored area. LLS data can be used to issue early warning alarms of incoming lightning activity to repair teams in the field, minimizing risks of accidents caused by lightning strokes. In sum, it is important to know the direction of a lightning front when conducting overhead line repairs or field testing.

2.4. POWER SYSTEM DESIGN

Lightning location systems can provide much more precise lightning density maps than the ones currently being used. Current lightning density maps utilize calculations from empiric factors and data from isokeraunic maps. The accuracy of such methods is limited and subject to factors specific to local regions. Improved results were obtained from networks of short range lightning counters (e.g. CIGRE 10 kHz counters). However, neither of these map types produce the level of accuracy and parameters that LLS lightning density maps can provide. The modern power system network design utilizes lightning density maps to aid in optimal overhead line route selection and the determination of adequate line protection equipment (e.g. line surge arresters, ground wires, etc.). With high resolution lightning density maps, it is possible to minimize the number of lightning strokes on overhead lines by selecting routes with a lower lightning stroke density. For existing overhead lines, critical route sections can be identified, and adequate protection can be selected, thus minimizing both cost and future power outages, as well as maximizing reliability [2].

3 INTERCONNECTING WITH OTHER SYSTEMS

The system for lightning data utilization in power systems requires interconnection with three external data sources. The system implements various communication interfaces, which can easily be upgraded. For lightning data input the system implements a client service to receive lightning data from lighnting data processing center. Data are obtained in 10 second intervals. The delay between the exact moment of a lightning stroke and the time the data is processed is less than 60 seconds.

For GIS input, a communication interface is available. GIS data contain geometries (points, lines, polygons) of power system facilities (e.g. overhead lines, substations, power plants, etc.). This enables a real-time interconnection to an external GIS database, making it possible to import and synchronize GIS data directly in case of a change. Where an external GIS database is not available the system utilizes a web based tool for GIS data import and management. GIS data enable the spatial correlation between lightning data and geometries representing power system facilities. It also enables the calculation of the exact distance of a fault location caused by a lightning stroke to the nearest substation (Figure 2). This information can be correlated with data from the distant relay protection.

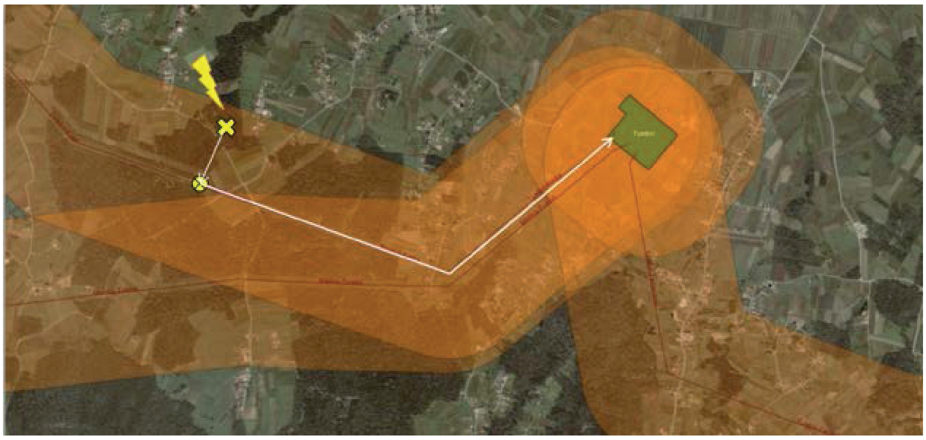


Figure 2. Spatial correlation of lightning stroke with overhead line alarm zones

For the input of data referring to failures in the power system (e.g. power outages, automatic reclosures, circuit breaker operation, distant relay protection operation, etc.) in real time, the system specifies communication interfaces specific to individual needs and conditions. Data from remote systems (protection relays, station computers, etc.) obtained through SCADA can be fetched by implementing clients for DAIS Alarms & Events or OPC server. By specifying which protection equipment and which signal types are to be correlated with lightning strokes, it is possible to determinate events caused by lightning strokes in near real time and present the information to dispatchers accordingly (Figure 3).

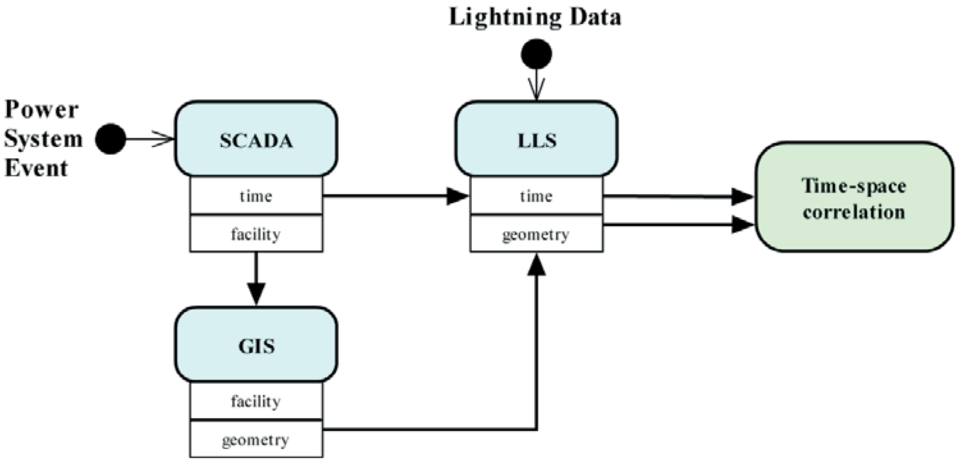


Figure 3. Time-space correlation schema

4 LIGHTNING CORRELATED FAULTS – CASE STUDY

4.1 Observed Lightning Activity

Two adjacent 110 kV overhead lines have been observed for faults and lightning activity in an area with heightened number of power outages. For calculation of lightning statistics, LLS data for the last three years (2009 – 2011) was available. Although a three-year period is too short to provide a creditable statistic; the obtained data show correspondence with other relevant sources and are sufficient to demonstrate the calculation principles. The LLS measured up to 48 lightning days per year (e.g. the isokeraunic map) for the area surrounding the overhead lines. Figure 4 shows the position of the monitored overhead lines and the isokeraunic map of lightning days for the observed area.

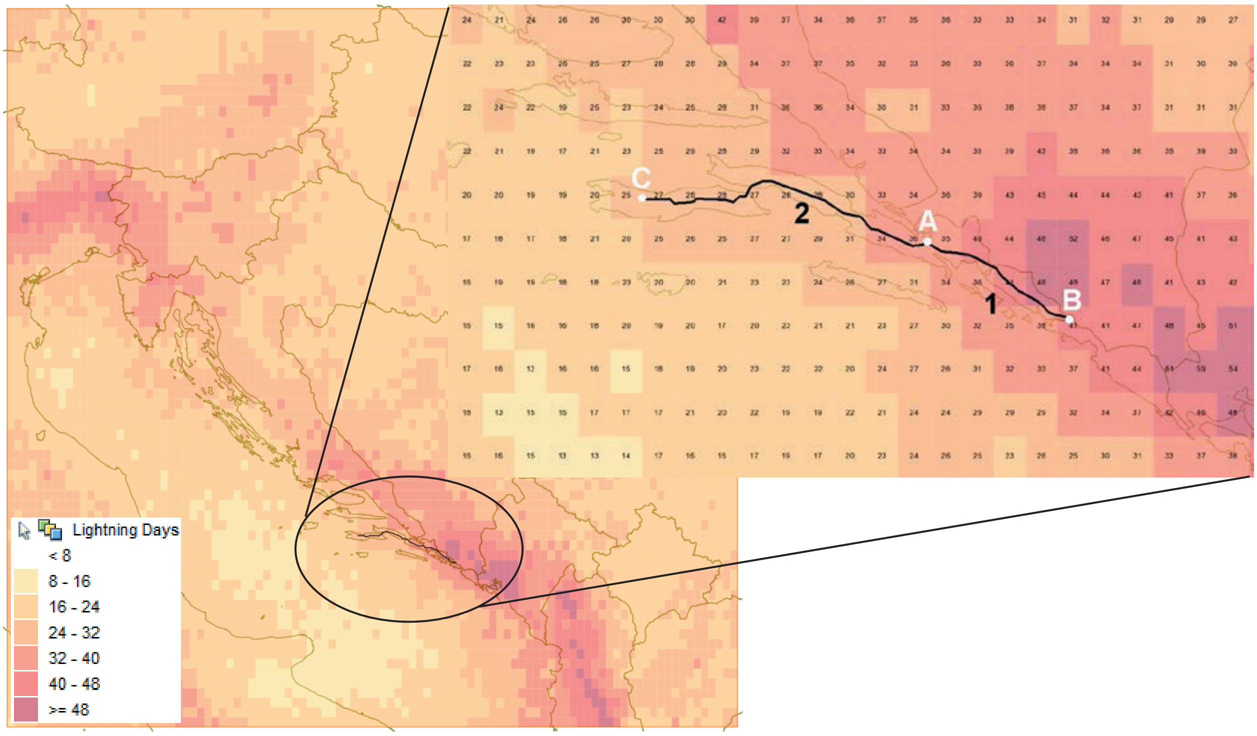


Figure 4. Map displaying isokeraunic map of lightning days (2009-2011) with monitored overhead lines (marked 1 and 2 on the map) and adjacent substation (marked A, B and C)

Lightning statistics for the area surrounding the monitored overhead lines (5720 km2) have been calculated for a 3 year period (2009-2011). Analyses show the number of cloud to ground (CG) lightning strokes per month with most of the lightning activity during summer months, Figure 5; CG stroke density (each stroke within a multiple stroke flash is represented individually), Figure 6; CG positive to negative stroke ratio, Figure 7; average and mean CG stroke amplitude, Figure 8 and Figure 9. The winter period is considered to be from November till April and the summer period from May till October. Analyses show much higher lightning activity in summer periods (CG stroke density of 11.01 N/km2/year) than in winter periods (2.78 N/km2/year) with a total of 6.89 N/km2/year for CG lightning strokes.

80% of total CG lightning strokes are detected during summer periods, but higher stroke amplitudes are measured during winter.

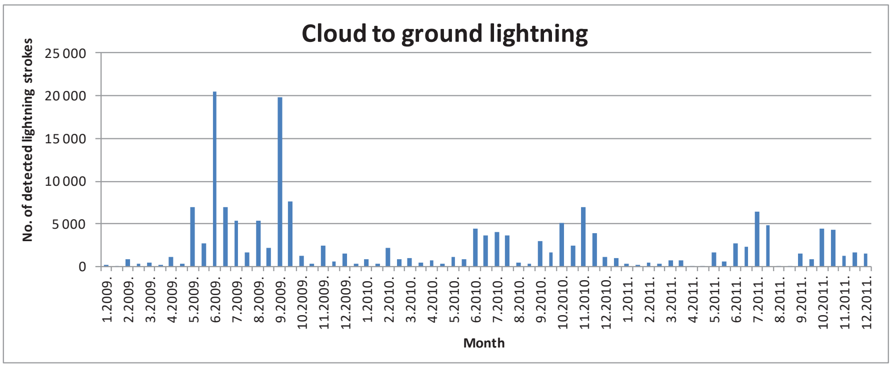


Figure 5. Number of lightning strokes per month

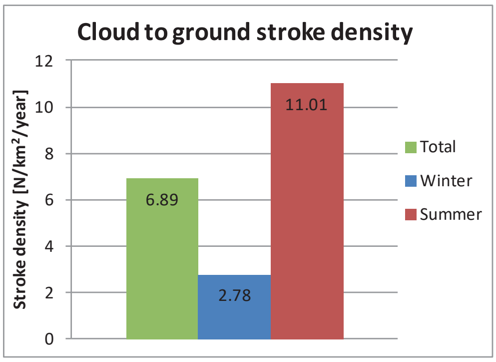


Figure 6. CG stroke density

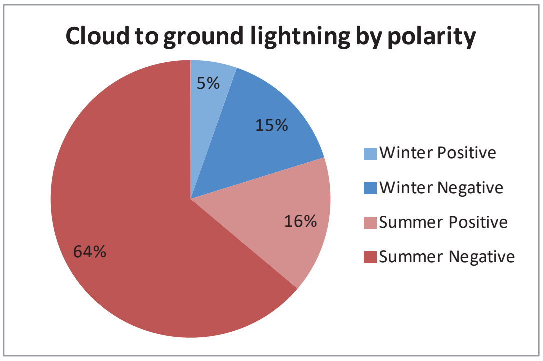


Figure 7. Ratio of CG stroke by polarity for winter and summer periods

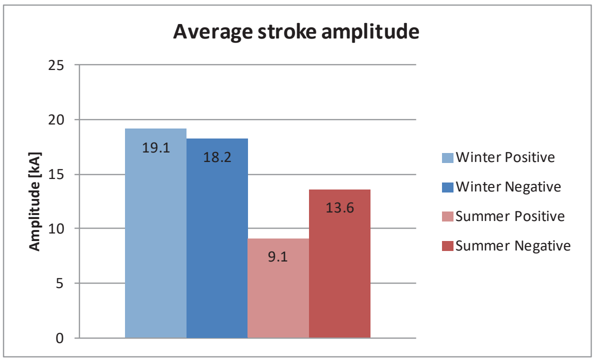


Figure 8. Average value of CG stroke current amplitude

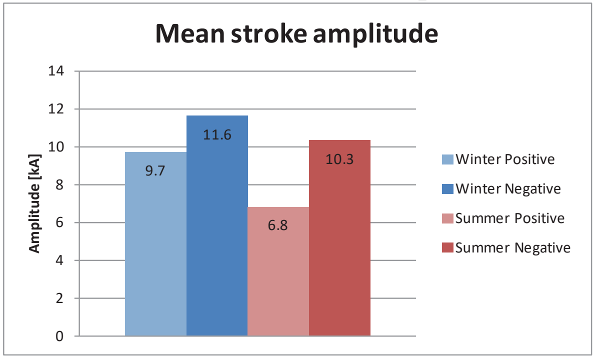


Figure 9. Mean value of CG stroke current amplitude

5 RELAY PROTECTION

For the protection of the observed overhead lines distant protection relays of the same type are used. The basic function of the distant protection device is the recognition of the distance to the fault with distance protection measurement. The relay protection device detects the line fault, determines the fault type and initiates an adequate single-pole or three-pole tripping as quickly, as possible. Since both the LLS and the relays are Global Positioning System (GPS) synchronized it is possible to correlate the data between lightning stroke times and fault detection times. For the purpose of time correlation the relay pick-up time is considered as the fault detection time since the relay is said to ‘pick-up’ when it changes from a de-energized position to an energized position. The relay pick-up is the first action following the point at which a relay has registered an event on the line. Fault determination follows the relay pick-up, after which commands to the circuit breakers may or may not be issued, depending on the duration and type of fault, as well as other parameters.

Laboratory measurements of the relay’s pick-up times were conducted for the relay type used o monitored overhead lines. The testing device was used as the source of the signal for relay device in known time point. Both the testing device and the relay were synchronized by GPS. The results of 21 measurements have shown that the pick-up time of the particular relay varies from 5 ms to 28 ms after the signal generation point (Table II). The average relay pick-up time value, after the signal generation is measured to be 17.05 ms.

Table II. Relay pick-up time delay statistics for 21 measurements

	Δt [ms]
Min	5
Max	28
Average	17
Median	17
Max-Min	23

6 CORRELATION ON 110 KV TRANSMISSION LINES

Correlation between lightning data and relay protection has been conducted on 110 kV transmission lines which is described in the following cases:

Case 1)

One of the observed events on a 110 kV overhead line (marked 1 in Figure 4) occurred on 29th July 2011 (Figure 10 and Table III). Distant protection relays in adjacent substations registered pick-ups at 06:35:12.763 and 06:35:12.769 local time. Pickups were registered on a single (top) phase of the overhead line. Commands to circuit breaker were issued and successful automatic reclosures procedures were executed on both sides of the overhead line. The LLS registered a lightning stroke in the overhead line alarm zone with peak amplitude of -18.7 kA at 06:35:12.754 local time. The lightning stroke precedes the registered pick-ups with a time difference of 9 and 15 ms. The fault locator measured the distance to the fault at 20.3 km / 24.1 km from the substations, where the LLS measured 18.4 km / 25.2 km.

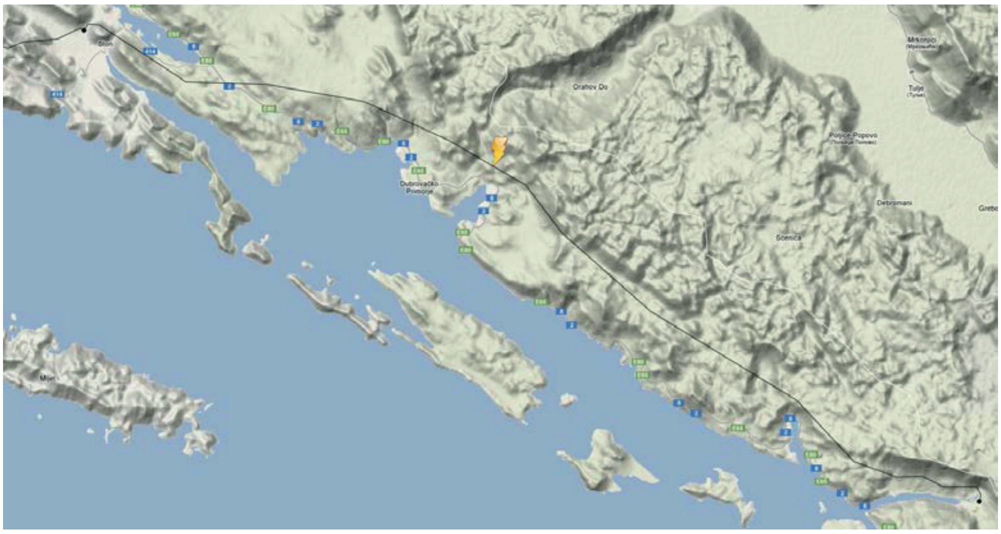


Figure 10. Lightning stroke causing line tripping

Table III Correlated data

Event date	29.07.2011.
Lightning time	06:35:12.754
Pickup time	06:35:12.763 / 06:35:12.769
Δt to pickup	9 ms / 15 ms
Lightning amplitude	-18.7 kA
Locating error	910 m
Distance to line	113 m
LLS Fault location	18.4 km / 25.2 km
Fault locator	20.3 km / 24.1 km
ΔL to fault locator	1.9 km / 1.1 km

Results gathered through survey of the given overhead line provided an adequate method for correlation between LLS data and relay protection data. A more comprehensive and detailed survey was conducted on an adjacent overhead line, which is described next.

Case 2)

The differences between the fault detection times of protection relays (average pick-up time) and the times of each individual lightning stroke recorded by LLS, which had caused the respective faults, were analyzed over a three-year period for the observed 110 kV overhead line (marked 2 in Figure 4). This overhead line passes through a region which has an average isokeraunic value 25-36 thunderstorm days per year, and is thereby exposed to frequent strokes of lightning.

Overhead line data are shown in Table IV. Construction and corresponding dimensions of the suspension tower of observed 110 kV line is depicted in Figure 11. The shield wire protects the line from all lightning strokes of return-stroke current exceeding the critical current, which is the maximal lightning stroke current that could strike the phase conductor beside the shield wire. The critical current is calculated according to the electro-geometric model, for the highest conductor of the suspension tower Nc7-T, and for different tower heights from ground to the lower arm. For the tower heights from 11.9 m to 23.45 m critical currents vary in range from 12.1 kA to 26.2 kA.

Table IV 110 kV overhead line data

Line	One-circuit
Tower	Steel-frame
Line length - ℓ [km]	78.573
Conductors	240/40 - Al/Steel
Shielding wire	ACS – OPGW
R_{d1} [Ω/km]	0.118
X_{d1} [Ω/km]	0.414
R_{01} [Ω/km]	0.349
X_{01} [Ω/km]	1.108

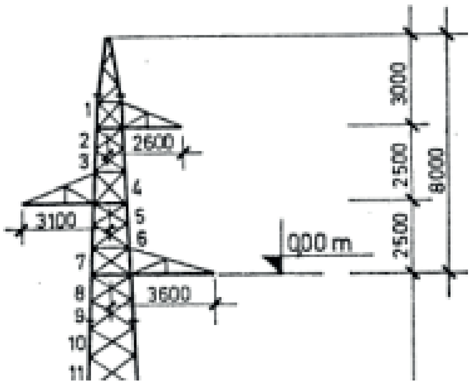


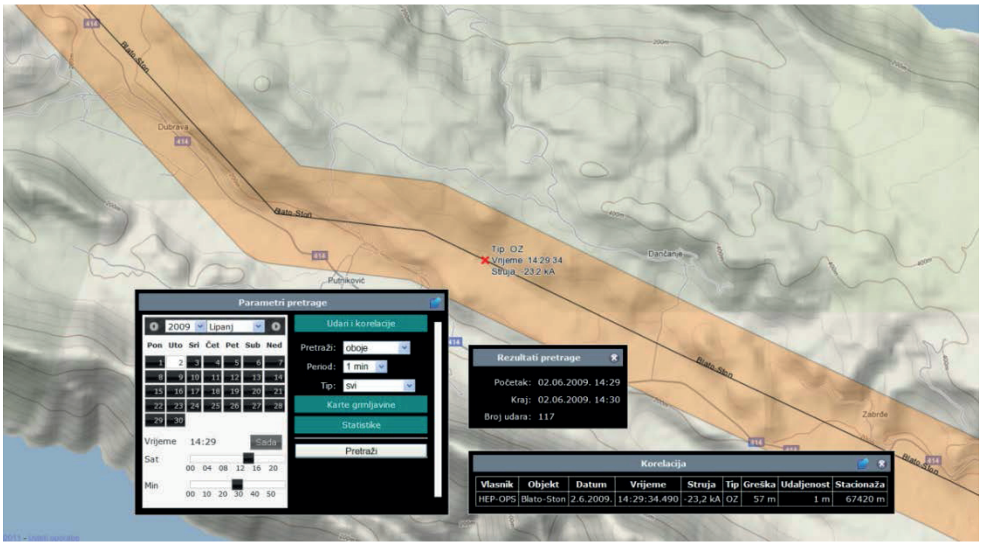
Figure 11 Suspension tower Nc7-T

During the observed three-year period 82 events were registered during which relay protection devices were activated.

From the correlation procedure were excluded those events for which the data about the exact time of the fault detection were not available, as well as the events for which LLS did not indicate any lightning activity.

Hence, the correlation was conducted for 59 events assumed to be caused by atmospheric discharges. The time difference of a maximum of 1 second between the fault detection time of relay protection devices and the time of a lightning stroke recorded by LLS has been determined as the basic precondition for the time correlation.

Figure 12 illustrates an example of the time correlation procedure by using the LLS. According to relay protection device data the fault which has occurred on 2nd June 2009 at the pick-up time of 14:29:34.521 caused the tripping of the line and its outage for 2 minutes. The fault occurred at a distance of 67.5 km according to the data of the fault locator function of the relay protection device of the respective overhead line. The LLS registered one lightning stroke which matches given criteria and which was possible to correlate with the observed relay protection fault detection. The correlated lightning stroke is of cloud-ground (CG) discharge type, stroke current amplitude of -23.3 kA, with a discharge occurrence time 14:29:34.490 and a distance of 67.429 km on the respective overhead line, with a location error of 57 m. Upon further analysis the time difference between the fault detection of the relay protection device and the lightning stroke recorded by LLS is 30 ms and the difference between the relay protection device fault location and the lightning strike location is 88 m, which is 0.1% of the total length of the observed overhead line.



Tip OZ
Vrijeme 14:29:34
Struja -23.2 kA

Pretraži: oboje
Period: 1 min
Tip: svi
Vrijeme 14:29
Sat
Min

Početak: 02.06.2009. 14:29
Kraj: 02.06.2009. 14:30
Broj udara: 117

Vlasnik	Objekt	Datum	Vrijeme	Struja	Tip	Greška	Udaljenost	Stacionaža
HEP-OPS	Blato-Ston	2.6.2009.	14:29:34.490	-23,2 kA	OZ	57 m	1 m	67420 m

Figure 12 Time correlation between a lightning stroke and the relay pick-up

The same correlation procedure has been conducted for all of the 59 faults registered by a relay protection device on the observed overhead lines with the assumption that they had been caused by atmospheric discharges. Six of the analyzed faults did not match the given criteria of the time difference of a maximum of 1 second between the fault detection time of the relay protection device and the time of the lightning stroke recorded by LLS although there were lightning strokes in the vicinity to the observed overhead lines and in the time period close to the fault detection time.

53 of the analyzed events matched the given criteria of the time difference and the time correlation between the lightning strokes and the protection device fault detection. The time differences between the lightning strokes recorded by LLS and the relay pick-up time for the 53 correlated and analyzed events (transmission line faults) are shown in Figure 13.

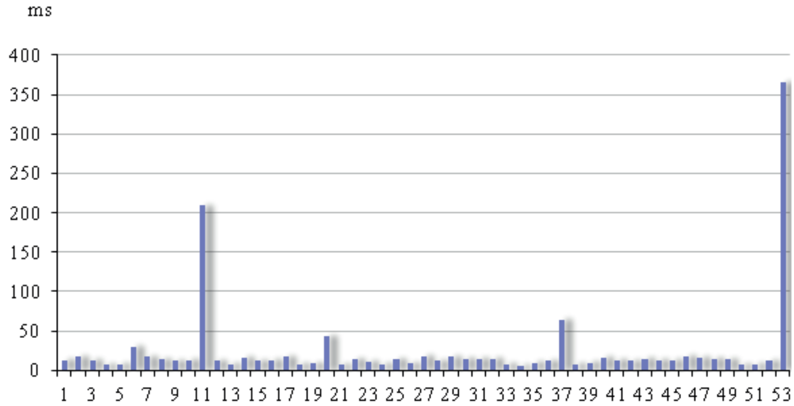


Figure 13 Correlated time differences between lightning strokes and relay pick-ups for 53 events

Figure 14 illustrates that the time differences vary between 6 ms up to 366 ms. Only three values are higher than 50 ms. The median time difference is 13 ms. The distribution of the correlated events according to time differences in the range of 1-100 ms is illustrated in Figure 14. Figure 15 depicts more precise the time differences up to 30 ms. It can be seen that most of the correlated events have a time difference between 10 ms and 20 ms (Figure 14), with 48 of the 53 correlated events (91%) with time difference up to 18 ms. Results correspond to laboratory measurements of the relay's pick-up times discussed earlier.

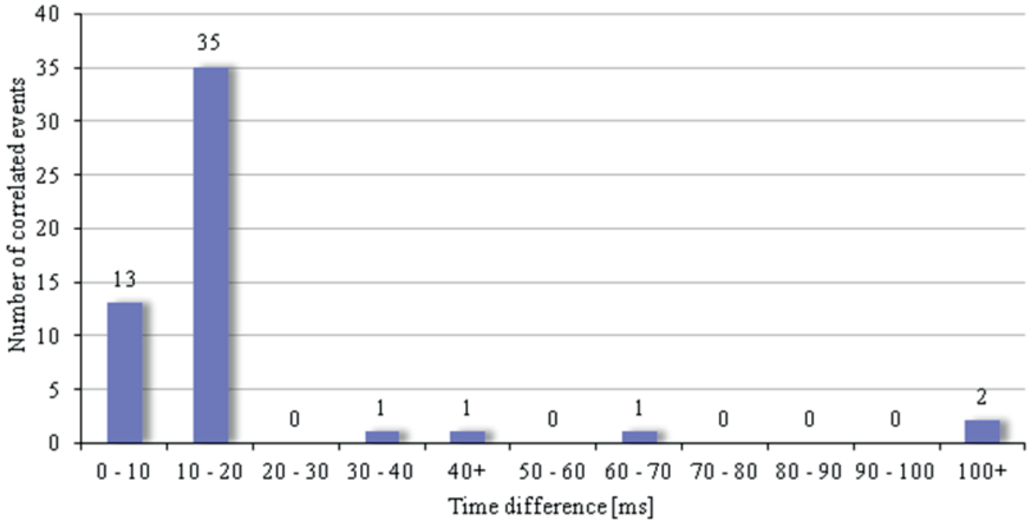


Figure 14 The distribution of correlated events according to time differences between the time of the lightning strokes and the relay protection device pick-up time

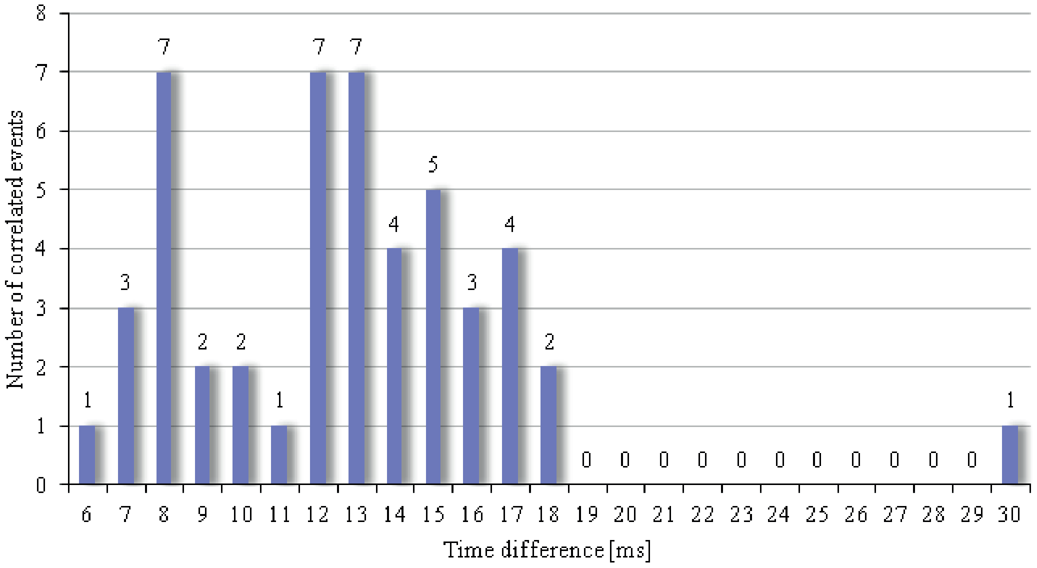


Figure 15 The distribution of correlated events according to the time differences between the lightning strokes and relay protection device pick-up time

For 37 of the events for which the time correlation has been determined and the protection relay data of fault location were available, the difference between the lightning stroke locations determined by LLS and fault locations determined by the relay protection has been analyzed. The results of spatial correlation have revealed the difference between the lightning stroke locations determined by LLS and the fault locations determined by the relays varies from 0.01% to 10.2% of total overhead line length, where the difference is between 1% and 2% for most of the correlated events, Figure 16. The average difference between the lightning stroke locations determined by LLS and fault locations determined by the relay protection device is 1.37% of total overhead line length.

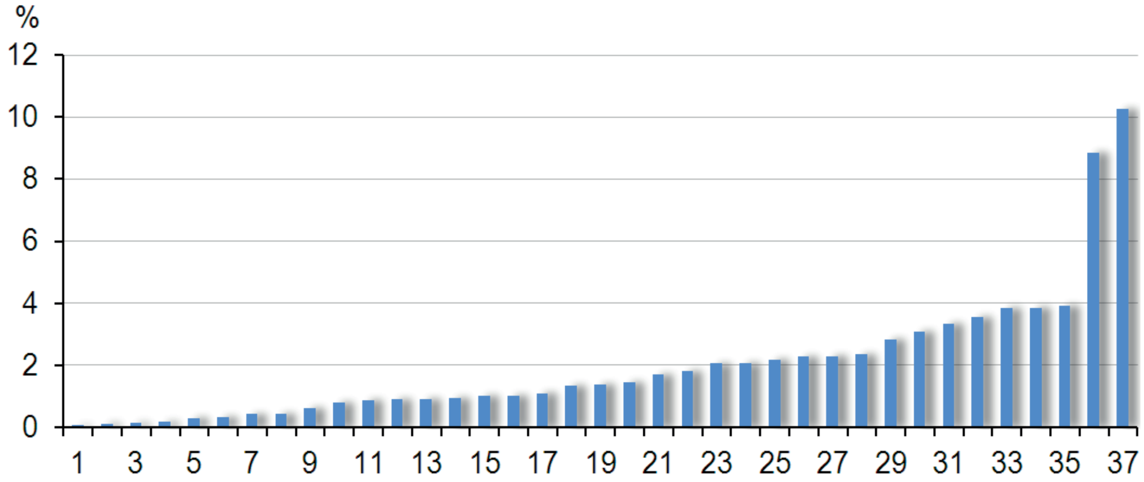


Figure 16 Differences between the lightning strokes locations determined by LLS and fault locations determined by the protection device

The analyses of the differences between the lightning stroke locations determined by LLS and fault locations determined by the relay protection device has been conducted under certain restrictive circumstances. The results of the analyses are influenced by the error of both the relay protection device fault location function and the LLS.

The accuracy of the fault location function of the relay protection device is affected by several factors. For example, the errors in current and voltage transformers which directly affect the distance estimation, uncertainties of the line constants, effects of untransposed transmission lines or influence of changing network configuration.

The observed overhead lines and the respective sensors of LLS are located in the coastal area. Since the sensors measure the magnetic flux directly as function of time the results of a lightning stroke location are influenced by the different conductivity (of land and sea) and, therefore, different field propagation effects [6].

Nevertheless, the results of the analyses of the differences between the lightning stroke locations determined by LLS and fault locations determined by the relay protection device can additionally prove the correlation between faults registered by the relay protection device of the overhead lines and lightning strokes detected by the LLS. Moreover, it could be concluded that the lightning stroke location determined by LLS could be used as information about the fault location on the overhead line, especially when the fault location function of the relay protection device is not available.

7 CORRELATION ON 35 KV DISTRIBUTION LINE

A similar procedure could be applied for correlation between outages and lightning strokes of medium voltage distribution lines. Table V shows a print of a station computer monitoring events on a 35 kV distribution line.

The outage of the 35 kV line was on 30th April 2011 in 17:53:16.647. The LLS registered a lightning stroke which matches the given time criteria of 1 second. The correlated lightning stroke was of cloud-ground (CG) discharge type, with stroke current amplitude of 117.2 kA, at 17:53:16.626 local time. The outage of another 35 kV line was on 24th July 2011 in 20:09:20.395. The LLS registered two lightning strokes which match given time criteria of 1 second. The correlated lightning strokes were of cloud-ground (CG) discharge type. The stroke current amplitude of -21.7 kA and -9.1 kA, with discharge occurrence time 20:09:20.174 and 20:09:20.188 respectively.

Table V Station computer event list

	Alarm List				
	Date	Time	Signal Group	Signal	Signal Value
1	30.4.2011.	17:53:16.647	35kV line 7SJ632	Switch off	Start
2	30.4.2011.	17:53:16.647	35kV line 7SJ632	I >> Swich Off	Start
3	30.4.2011.	17:53:16.661	Voltage 0.4kV, 50Hz	Outage	Start

8 CONCLUSION

Real time lightning tracking can be an effective asset in the management of spatially distributed systems exposed to atmospheric conditions. Such systems represent a powerful tool in the design, protection and control of power systems. Their application can also be found in numerous other systems, including telecommunication, radio and television networks, pipelines, insurance companies, meteorological services, fire fighting agencies, etc.

Nowadays LLs are widely used by many transmission and distribution operators. By utilizing custom software tools and analysing lightning data, correlation with relay protection can be conducted. Correlating relay protection data of faults in the power system with lightning data, useful information for identifying and locating the fault cause can be obtained. Utilizing GPS synchronization in relay protection and LLSs a high degree of success in time correlation is achieved. Lightning strike locations determined by the LLS, correlated and identified as cause of line faults, match with fault locator data within satisfactory tolerance.

The time correlation between line faults and lightning strikes revealed that the protection relays detect faults on the protected transmission line generally with time difference up to 28 ms after a lightning strike, which corresponds to the laboratory measurement results of the relay's pickup time.

The spatial correlation between the faults on the transmission line and the lightning strikes indicate that the median value of differences between the fault location and the lightning strike location is 1,37 percent of total transmission line length of the observed line. This result is obtained by several factors that affect the accuracy of the fault locator, as well as the LLS.

It has been indicated that the time correlation can provide information on the fault cause and the lightning data can serve as information on the fault location.

Results confirm the efficiency of correlating protection relay data with LLS data for the purpose of identifying fault cause. This new information contributes to minimizing the time for identifying outage cause and conducting repairs, which refers on improving power quality.

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