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Improving and advance control, maintenance and planning of transmission power system with lighting location systems data

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SUMMARY

Complete lightning data were collected using lightning locating system (LLS) in Croatia by the Croatian transmission system operator (TSO). The LLS correlation system runs as a part of the National control center's utility function, collecting lightning data and correlating with network data in real-time. The real-time lightning correlator function relies upon SCADA to acquire network faults, circuit breaker (CB) operations and relay protection data. Geographic information system (GIS) functionality was integrated into the LLS correlation system in order to make the spatial correlation between lightning strokes and network events. Lightning data are available since 2009 and lightning correlated faults data since 2013, providing full eight and four years, respectively, of precise and comprehensive data inputs from LLS, SCADA and GIS systems. Network planning processes are improved by using statistical and spatial analyses results of lightning correlated data as additional inputs for transmission line reconstruction, modernization and designs of new transmission lines.

Lightning statistics for the Croatian transmission network will be presented in this paper to prove a context for the lightning related statistics of the observed transmission network. Statistical analyses on lightning correlated data are conducted taking into account 339 transmission lines of 110, 220 and 400 kV, with total length of 8 458 km. Latest improvements of the system will be presented as well as an example of spatial analyses of transmission lines containing critical segments.

KEYWORDS

Lightning locating systems, transmission power system, power system control, lightning induced faults, correlation, CB operations

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1. INTRODUCTION

The Croatian lightning location system is implemented in the National dispatch center of the Croatian TSO in Zagreb. The correlation process correlates the circuit breakers (CB) operations in transmission network with lightning strokes recorded by LLS. The results of these correlations present in detail critical segments of the transmission lines that have high lightning stroke density and identify lightning induced faults. The correlated data is further statistically processed and new information about network events caused by lightning strokes is obtained. Croatian LLS and the correlation process are being improved and adapted to Croatian TSO demands so that data obtained enables advanced planning, control and maintenance of the transmission system.

In this paper, the latest improvements of LLS are presented: update of Geographic Information System (GIS) data for all the transmission lines, increased detection sensitivity in LINET system, new algorithm that processes network topology data, notifies if changes happen and automatically downloads new scheme. Example of spatial analysis of a critical transmission line segments and identifying close lightning strokes are shown and some statistical results for Croatian transmission network, for 2016 are given.

2. IMPROVEMENT OF THE LLS

2.1 Improved detection sensitivity within LINET system

Lightning stroke generates magnetic field that has maximal value roughly proportional to stroke current amplitude. Maximal value of magnetic flux density that sensor can record is determined by the attenuation of the electromagnetic (EM) wave since it propagates over the surface with determined conductivity. When attenuated EM wave reaches the sensor, its amplitude has to be higher than sensor threshold, in order to be recorded by sensor. This depends on signal amplification, threshold adjustment and local disturbances. In order to locate the stroke, it is necessary that the same stroke is recorded by several sensors. The sufficient number of sensors that should record the same stroke in order to locate it is determined by the stroke-sensor distance and the method for determining the location. LINET system uses *Time of Arrival* (TOA) method and the minimal number of sensors that should record the same stroke is 4.

Lightning location system detection efficiency (*DE*) depends on distance between sensors, network topology, sensor sensitivity and signal processing and filtering. For the exact calculation of the detection efficiency, it is necessary to know the cumulative probability of current amplitude distribution, sensor threshold adjustment, electromagnetic wave propagation conditions (ground conductivity) and the method for determining the stroke location.

Dependence of the *DE (I)* and the distance *D* at particular current amplitude *I* is determined with maximum detection efficiency DE_{max}, sensor treshold at D_1 and sensor sensitivity limit at D_2 (Figure 1.a). Distances D_1 and D_2 depend on current amplitude *I* and signal attenuation (Figure 1.b). In reality, the sensor will not detect every single stroke that occur (*DE* = 100%) whose maximum magnetic flux density lies between the treshold and sensitivity limits.

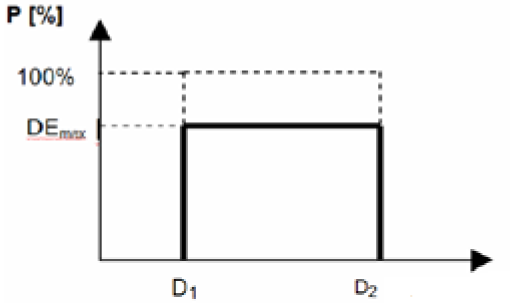

Figure 1.a *DE* of one sensor

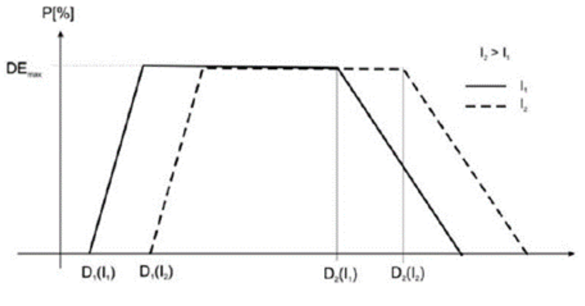

Figure 1.b *DE* for two different current amplitudes

The probability that the sensor detects the stroke is defined by the *DE* function of each sensor, DE_i. Since all the sensors are at different locations, the distances between each sensor and stroke locations are different, hence the efficiency DE_i is different for each stroke. Assuming that each sensor reacts independently, the DE_i values are independent of each sensor. In order to determine detection efficiency for the whole sensor network, the area covered by sensors is divided in multiple rectangular elements. Furthermore, for the central point of each rectangular element, for each possible amplitude *I*, the *DE* of each sensor is determined. The detection efficiency for an amplitude is the sum of all probabilities for minimum of 4 (determined by TOA method) or more sensors that recorded the stroke. If the probability that one sensor has not recorded a stroke is defined as $Q_i = 1 - DE_i$, then the detection efficiency in one rectangular element, for any number (4 or more) of sensors is defined as follows:

$$DE_{ef} = \sum_{k=m}^{n} \left[\binom{n}{k} \times (DE_i)^k \times {Q_i}^{(n-k)} \right]$$

The overall detection efficiency of the network is calculated as average value of detection efficiencies of all rectangular elements.

In LINET system, during the 2016, detection sensitivity was improved and detection efficiency for strokes with smaller amplitudes increased. In reality, strokes with small amplitudes occur very often and consequently, the increased sensitivity of the detecting increased the total number of detected lightning strokes in 2016. This resulted in shifting the median current amplitudes value towards lower amplitudes. Cumulative amplitude distribution for negative cloud to ground strokes is shown in Figure 2. Table 1 shows the median amplitude values of detected cloud to ground lightning strokes 2009-2016. According to IEC norms, only cloud to ground strokes are analyzed since they make the majority of all strokes.

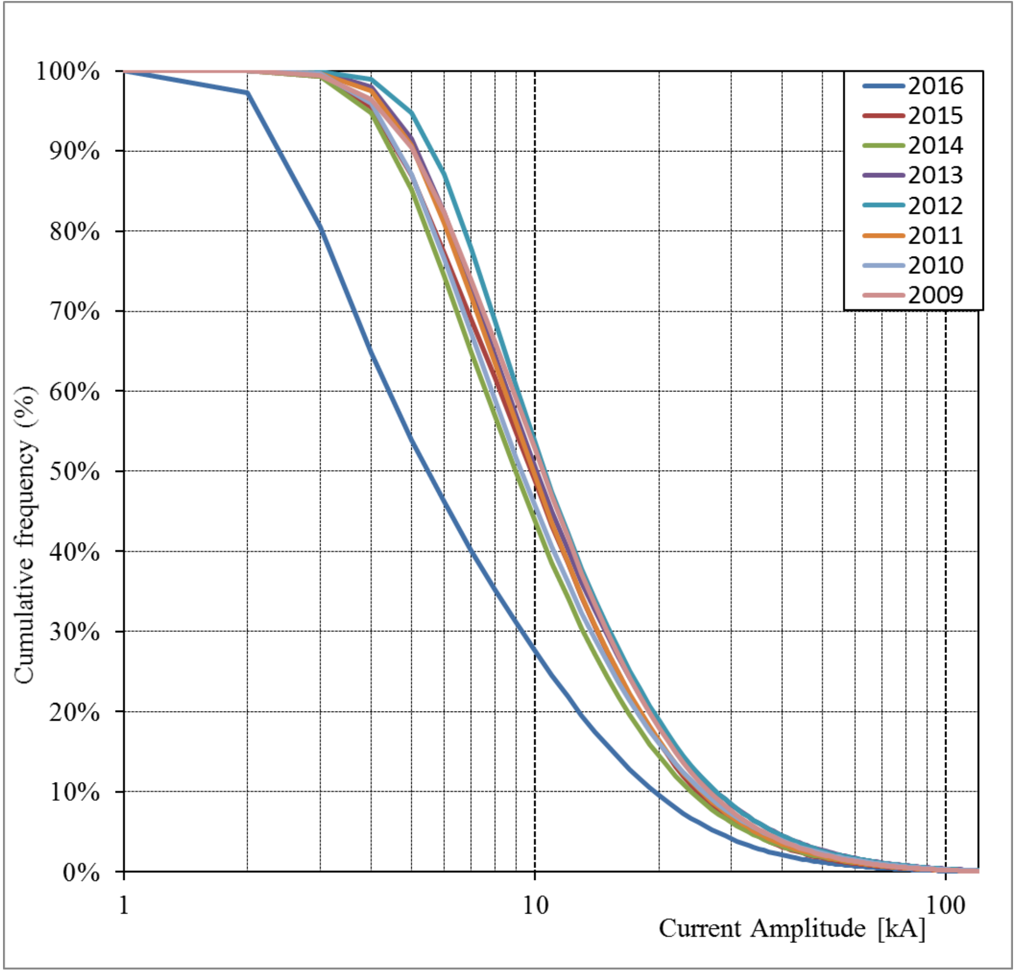

Figure 2. Cumulative amplitude distribution of negative cloud to ground strokes 2009-2016

Table 1. Median values of amplitudes 2009-2016

Year	Median current amplitude value [kA]
2009	9.3
2010	9.0
2011	9.5
2012	8.8
2013	9.0
2014	8.0
2015	8.0
2016	4.6

2.2 New algorithm for processing network topology data

The correlation process started in 2013 after SCADA was implemented by Croatian transmission system operator. This made network events available to LLS for correlation process. However, the input of GIS data was done manually, as well as all changes in network scheme. In 2016 new algorithm that processes network scheme data, notifies if changes happen and automatically downloads new scheme, was implemented in Croatian LLS. When network scheme is changed, the list of signals is also checked and in case of change, valid signals are obtained from chronological events list (CEL) in SCADA. The described improvement of the correlation algorithm ensures automatic adaptation of the actual scheme, i.e. transmission line - line bay in substation - circuit breaker relations and circuit breaker signals - corresponding protection relay signals relations. The algorithm uses the object hierarchy to process network scheme, i.e. to relate circuit breakers to line bays, line bays to corresponding transmission lines, transmission lines to substations, etc. The hierarchy used is shown in Figure 3.

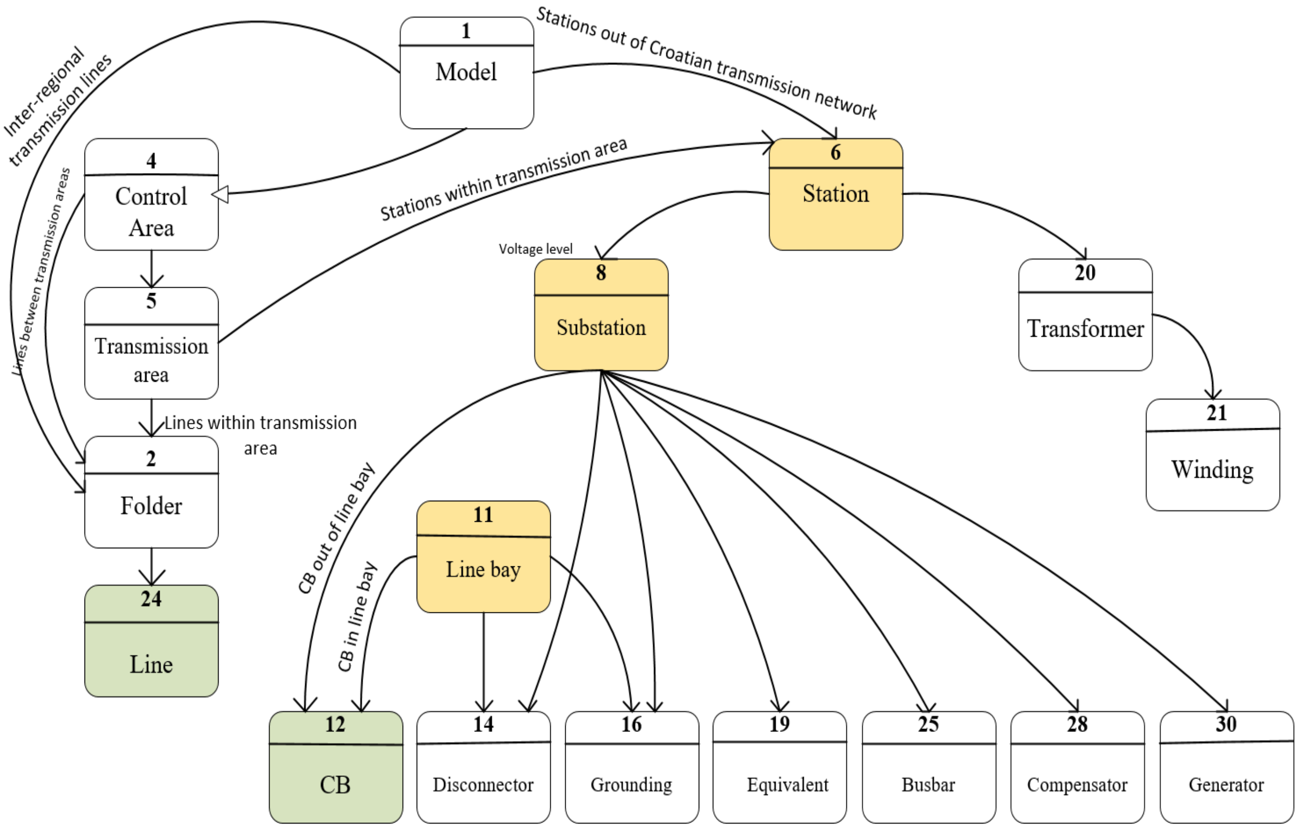

Figure 3. Objects hierarchy used for processing network scheme data

The line bay and transmission line data are copied from the Utility Data Warehouse (UDW) database of the SCADA system to LLS. LLS periodically checks the changes in the SCADA network scheme and, in case of change, alerts the administrator. The administrator confirms the changes and copies them to LLS. The algorithm, using hierarchy shown in Figure 3, retrieves the relation between the following objects:

- transmission lines,
- disconnectors,
- circuit breakers,
- circuit breaker and relay indications and
- line bays.

These relations enable LLS to associate the circuit breaker and line bay geographically (connecting GIS and SCADA data) and furthermore to relate these to circuit breaker and relay indications from SCADA event list, i.e. CEL list.

3. ADVANCED CONTROL, MAINTENANCE AND PLANNING OF TRANSMISSION POWER SYSTEM

3.1 Cloud to ground stroke density maps

In order to identify critical segments of the transmission lines, the stroke density maps are made. Only cloud to ground strokes were used to create density maps, as explained in previous section for presenting cumulative amplitude distributions. It is important to distinguish stroke density and flash density maps. It is known that one lightning flash can content multiple strokes. Flash multiplicity factor (FMF) is defined as the ratio between the number of all lightning strokes, first and subsequent strokes, and the number of lightning flashes. The Croatian LLS groups lightning strokes into one flash if the distance between stroke locations is smaller than 2 km and the time difference between strokes does not exceed 200 ms.

The mean cloud to ground flash density in 2016 in areas around the transmission lines is 16.092 [strokes / km^{2}year], i.e. 9.264 [flash / km^{2}year], and the absolute maximum measured in a transmission lines corridors is 167.982 [strokes / km^{2}year], i.e. 96.708 [flash / km^{2}year] at the area of 110 kV transmission line *DV 105-RI/ST Obrovac-Gračac*. The absolute maximum of 167.982 [strokes / km^{2}year] is rather high and it was discovered that such high density value is due to television transmitter located in proximity of mentioned transmission line. Comparing the densities in 2016 to previous years, it is important to outline that the higher flash densities are also related to improvement of detection of lightning strokes with smaller amplitudes within LINET system.

3.2 Alarm zone definition

The alarm zone is defined based on total location error value. The radius of the alarm zone is calculated as $R_{zone} = 2\times L_{\mathrm{total}} = 1000$ m. Figure 4 shows an example of an alarm zone. Croatian LLS allows to define the radius of each alarm zone separately. The surfaces of alarm zones are calculated in order to get stroke densities in alarm zone areas.

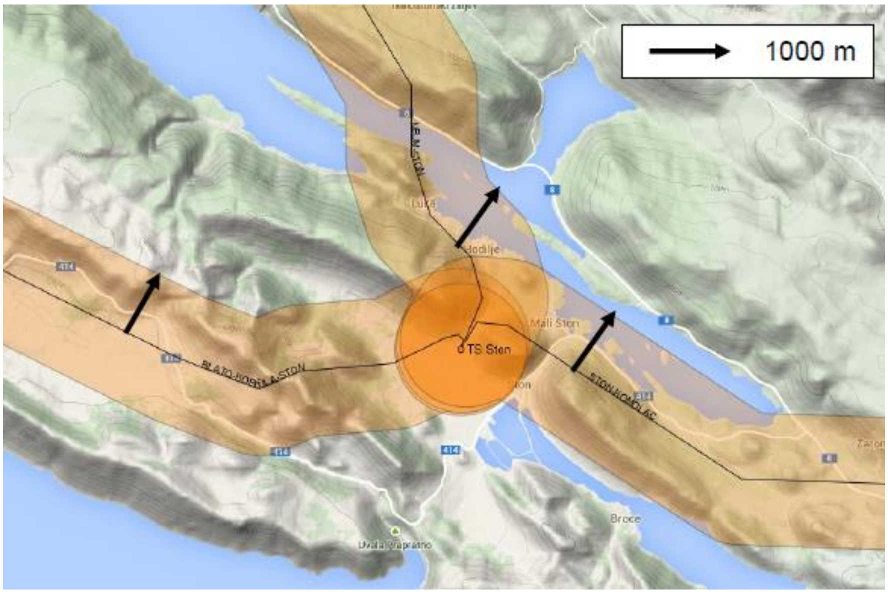

Figure 4. Alarm zone example

3.3 Identifying critical segments of the transmission lines

When identifying critical segments of transmission lines, the stroke density map is used and all first and subsequent strokes are taken into account. The critical segments of transmission lines are the ones with high stroke densities in their alarm zone. The spatial analysis of lightning stroke density in alarm zones of transmission lines is done using high-resolution stroke density maps with approximately 1 km x 1 km spatial resolution (0.01º of latitude and longitude in World Geodetic System). Each 1 km x 1 km area has determined stroke density as in Figure 5.

The frequency of each density along the alarm zone of a transmission line is observed to identify critical segments and potentially endangered transmission lines. It should be noted that in example shown in Figure 5, the stroke density is higher in area where transmission line passes close to a wind power plant. It is interesting to compare the stroke densities of this area in years before installing wind turbines and after.

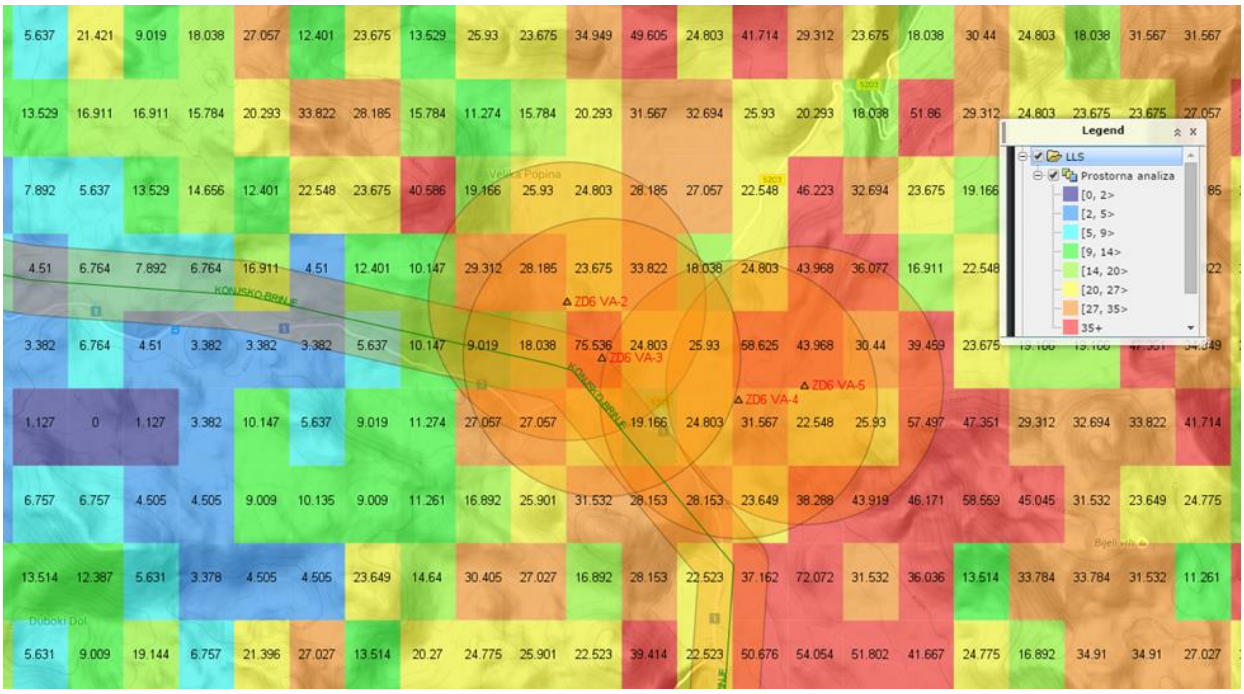

Figure 5. Example of a high-resolution stroke density map

Further, the density classes are defined with the step of 5 [strokes / km^{2}year] and the 1 km x 1 km areas in alarm zones are sorted in these density classes. Figure 6 shows stroke density classes and corresponding number of transmission lines that contain the particular class. For 2016, 80 [strokes / km^{2}year] was taken as limit for very high stroke density, and 21 transmission line that passed through very high stroke density were studied in detail. The most exposed transmission line to lightning strokes in 2016 is 110 kV transmission line *DV 105-RI/ST Obrovac-Gračac* with highest stroke density measured in its alarm zone of 167.982 [strokes / km^{2}year] is shown in Figure 7 as an example of detailed spatial analysis.

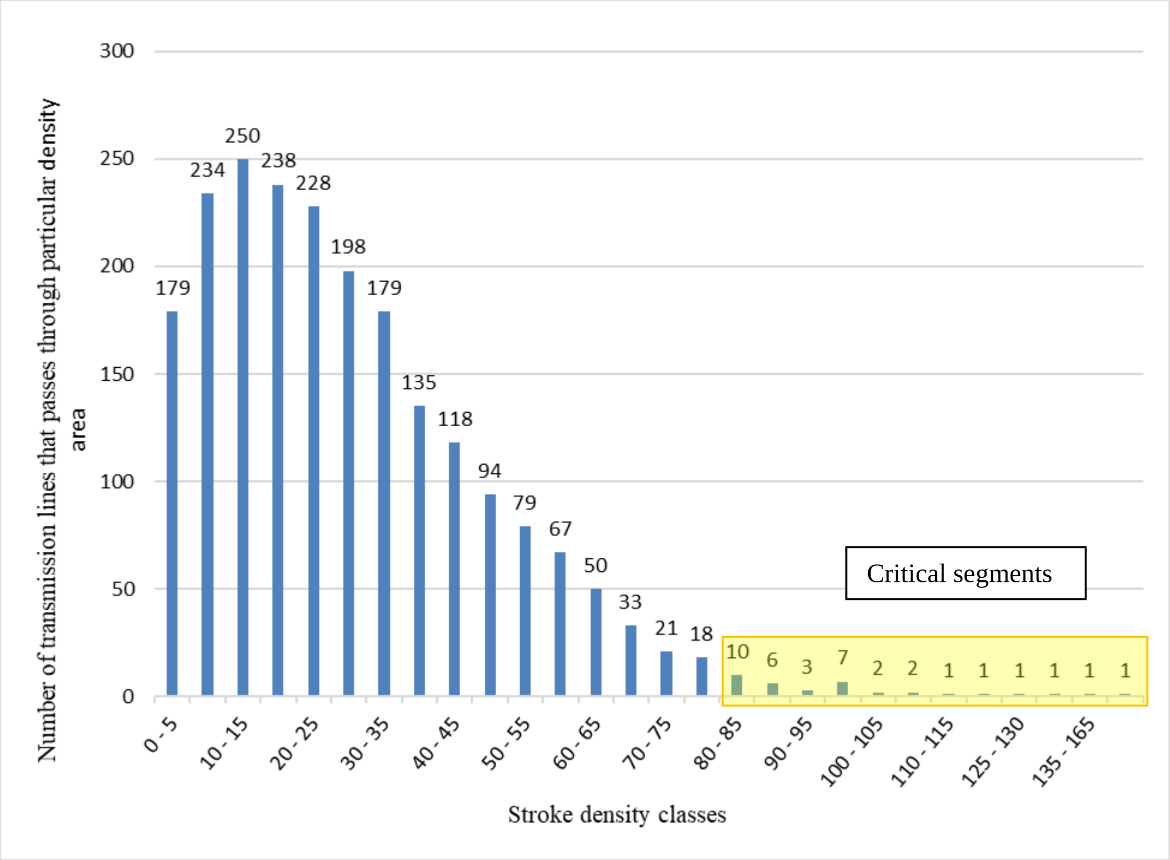

Figure 6. Transmission line segments sorted according to lightning strokes exposure in 2016

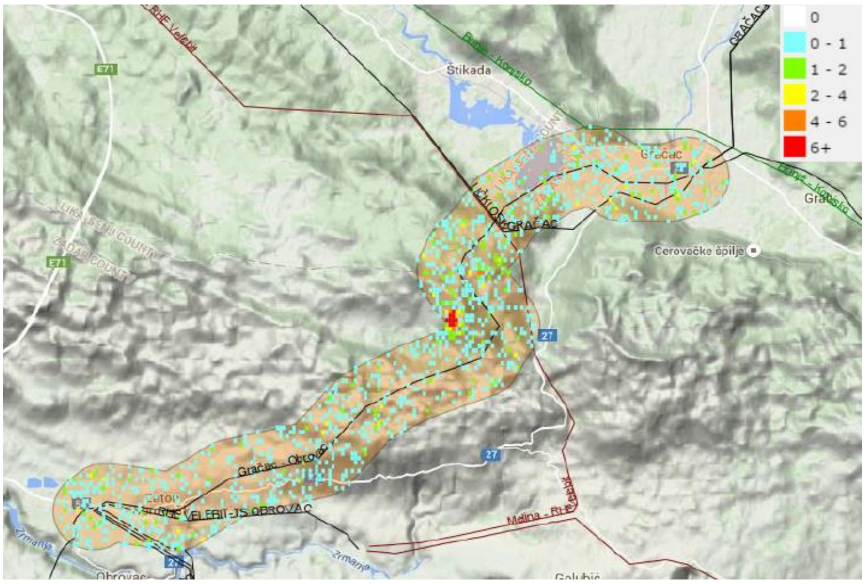

Figure 7. The most exposed transmission line to lightning strokes in 2016

3.4 Close lightning strokes

Under normal circumstances, the circuit breaker (CB) has to carry the current and energize or de-energize sections of the transmission network. At the moment that somewhere in the network a short circuit appears, the CB is the only high-voltage apparatus to protect the network. If the short-circuit current is not cleared immediately, the backup protection systems will trip a larger part of the network, leading to an outage of more transmission lines, busbars and substations. Moreover, the fault must be quickly removed since otherwise dynamic stability problems in the entire power system may occur. Consequently, the requirements for CB performance and reliability are very high [7].

In order to determine the CB maintenance and life-cycle strategy, Croatian LLS started to identify circuit breaker operations correlated to close lightning strokes. Close lightning stroke can cause short-line faults, which can bring the CB in difficult mode of operation or damage it. Though close lightning strokes can have amplitudes lower than CB interrupt capacity, it can happen that circuit breaker fails to trip due to high steepness of the transient recovery voltage that causes high-frequency oscillations. During the CB lifespan, the interrupt capacity decreases due to aging, wear, number of operations after faults, etc. Identifying close lightning strokes that can cause short-line faults is thus useful in CB maintenance and life-cycle strategy.

3.5 Critical distance

Close lightning strokes and short-line faults are defined as all strokes and faults that happen within the critical distance from CB. Critical distance is the distance at which the lightning current steepness is the greatest. Moving away from the critical distance to greater distances, the current steepness decreases and does not bring CB in difficult mode of operation. Critical distance depends on the line and CB parameters, hence it is different and should be calculated for each transmission line. In Croatian LLS, these critical distances are not calculated. Instead, one critical distance is estimated and used for every transmission line and CB. Initial estimation of critical distance is 2 000 m. To compensate the locating error, the initial estimation is increased for alarm zone radius, so the final critical distance that was taken into account is 3 000 m.

During 2016, 57 CB operations were correlated to close lightning strokes. Within the same line bay, the largest number of CB operations correlated to close strokes is 3.

3.6 Lightning statistics for Croatia in 2016

Statistical analyses on lightning correlated data in Croatia are conducted taking into account 339 transmission lines of 110, 220 and 400 kV, with total length of 8 458 km (

Table **2**). 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, taking into account single-strokes as well as multiple-strokes. Furthermore, Croatian LLS sorts subsequent strokes to flashes using time and location criteria. It is important to outline that faults can be temporary or permanent. Temporary faults are automatically cleared. Croatian LLS started recording CB auto-reclosures and the data will be available for 2017. Data shown in tables below refers to CB operations after permanent faults.

During 2016, 262 CB operations were correlated to lightning strokes in Croatian transmission network. Out of total 262 correlated operations, 3 occurred in 400 kV, 21 in 220 kV and 238 in 110 kV transmission lines, as shown in Table 3. Median lightning current amplitude that caused CB operation was 35.0 kA. Minimal lightning current amplitude that caused CB operation was 1.7 kA and maximal, 175.2 kA occurred at *DV 133-ST Blato-VE Ponikve* transmission line 110 kV. Croatian transmission network is divided in 4 transmission areas, and as it could have been predicted, coastal transmission regions Split and Rijeka had the most correlated CB operations, 146 and 98 respectively, while transmission regions Osijek and Zagreb had 12 and 6 correlated CB operations, respectively. Table 4. gives comparison of number of all recorded CB operations, number of CB operations correlated to lightning strokes and number of CB operations due to close strokes by voltage level. Out of the total of 11 918 CB operations, 262 were correlated to lightning strokes, 57 being close ones.

Table 2. Spatial correlation of lightning strokes and transmission lines for 2016

		400 kV	**220 kV**	**110 kV**	**Total**
2016	No. of transmission lines	15	27	297	**339**
	Transmission lines length [km]	1 676.225	1 468.082	5 313.616	**8 457.923**
	Alarm zone surfaces [km^2]	3 391.696	3 014.185	11 424.409	**17 830.290**
	No. of strokes	91 908	84 993	290 267	**467 168**
	No. strokes / 100 km of transmission line	5 483	5 789	5 463	**5 523**
	Stroke density [stroke / km^{2}year]	27.10	28.20	25.41	**26.20**

Table 3. Correlated CB operations by voltage levels and transmission regions

Voltage level	Number of correlated CB operations	Transmission region	Number of correlated CB operations
400 kV	3	**Split**	146
220 kV	21	**Rijeka**	98
110 kV	238	**Osijek**	12
Total:	262	**Zagreb**	6
		Total:	**262**

Table 4. Total CB operations vs. correlated CB operations

		400 kV	**220 kV**	**110 kV**	**Total**
2016	No. of line bays	33	53	483	569
	Total No. of CB operations	390	1 407	10 121	11 918
	No. of operations / No. of line bays	20.954	26.547	11.818	20.946
	No. of correlated CB operations	3	21	238	262
	No. of correlations / 100 km line length	0.179	1.430	4.479	3.098
	No. of operations CB due to close strokes	1	2	54	57

CONCLUSION

Lightning related data were collected and correlated in order to improve planning, control and maintenance of transmission network. The improvement of the LLS system enables higher efficiency of correlation process. In 2016 detection efficiency was improved and consequently higher number of lightning strokes with smaller amplitudes are being recorded. New algorithm for automatic processing of network topology was implemented which enabled automatic update of signal and network topology changes. After processing correlated data, critical segments of transmission lines are identified, as well as close strokes that can bring switching devices to difficult mode of operation or damage them. The mean cloud to ground flash density in 2016 in areas around the transmission lines is 16.092 [strokes / km^{2}year], i.e. 9.264 [flash / km^{2}year], and the absolute maximum measured in transmission lines corridors is 167.982 [strokes / km^{2}year], i.e. 96.708 [flash / km^{2}year]. It is noticed that high stroke density areas are often near wind turbines, television transmitters, etc. Out of 467 168 strokes and 11 918 CB operations recorded by the LLS and SCADA, 262 CB operations were correlated to lightning stroke, 57 being caused by close strokes. As expected, coastal regions had more lightning induced CB operations.

Statistical data is formed according to Croatian TSO needs and demands. Data that Croatian LLS provides proves a context for the lightning related statistics in planning, control and maintenance of observed transmission network.

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