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Study of Time Correlation Between Lightning Data Recorded by LLS and Relay Protection

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***Abstract* — Paper deals with the time correlation between lightning strokes and protection relay pickups. On a line fault, the relay pickup is the first action registered by the protection relay. For this, the pickup time is taken for correlation with lightning data available from the lightning locating system (LLS). The conducted studies have shown the time differences between a lightning stroke and a relay pickup to be up to 28 ms in 85% of the observed cases.**

Keywords – lightning locating system, lightning strike, relay protection, relay pickup, line fault, time correlation

I. 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.

Power and electrified railway companies started utilizing LLS relatively late and only after LLS were sufficiently mature. In the 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 have been largely eliminated. Today, the modern LLS are increasingly used by power and distribution operators [1], [2]. 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 networks with lightning strokes;

b) in establishment, management and monitoring of power systems;

c) in warning of coming lightning fronts;

d) in choosing the route of overhead lines and ways to protect them from lightning [3].

In this paper, emphasis will be given to the application in correlation between faults and outages in the power network and lightning strokes. LLS data can be correlated with data of faults and outages in power network, which may contribute to power quality. 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. Comparison with LLS data shows that not all faults and outages during a thunderstorm are caused by lightning. A certain number of outages could be caused by strong winds during a thunderstorm causing two-phase or one-phase short circuits. An efficient method for determining the real number of circuit breaker tripping and re-closing caused by lightning is the correlation between fault time and location from the protection relay with LLS data. Relay pickup is the first signal upon registering a line fault, thus is used for the time correlation with lightning data.

II. SPATIAL CORRELATION

To enable the spatial correlation between the lightning stroke location and the monitored power lines, geographic information system (GIS) data of power lines are used. GIS data of the power lines provide spatial information of the power line position and shape. Furthermore, as the LLS provides information of lightning stroke location as a 2D point and a radius which determinates the 50% location probability, an alarm zone with 2 km radius around the power line is constructed to make sure all relevant lightning stroke candidates are processed. Lightning strokes spatially correlated within the power line alarm zone will be analyzed further. This spatial filter is used as the first step in the correlation process.

Moreover, it is possible to compare the lightning stroke locations determined by the LLS and the relay protection device data of fault locations where available. There are certain restrictive circumstances under which these analyses have been conducted since the differences between the lightning stroke locations and fault locations 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 estimate or uncertainties of the line constants; the effects of untransposed transmission lines or influence of changing network configuration.

Since the sensors of LLS measure the magnetic flux directly as a 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 [4]. This is particularly the case with the observed overhead lines and the respective sensors which are located in the coastal area.

Nevertheless, the correlation between the lightning stroke locations determined by LLS and fault locations determined by the relay protection device can additionally validate the correlation between faults registered by the relay protection device of the overhead lines and lightning strokes detected by the LLS.

III. Time Correlation

How much time is needed from the point at which the lightning stroke hits the transmission overhead line, followed by the insulator flashover, to the point where the fault is cleared?

This question is particularly connected to cases involving multiple lightning strokes within the corridor of the overhead line occurring in brief time intervals. In such cases it is difficult to determine which stroke of lightning caused the overhead line to trip. Modern LLSs use GPS time synchronization with accuracy of ±100 ns [4]. The relay protection devices usually display the moment of their operation in the range of 1 ms. Hence, it is possible to determine the time of the lightning stroke within a time interval of 1 ms, that enables an improved time correlation capability, comparing to values reported in [5]-[7]. A certain time is needed to detect the fault and initiate the tripping command by a relay protection device. The relay protection devices need to detect the fault on the line, determine the type of fault and initiate an adequate single-pole or three-pole tripping as quickly as possible. Moreover, the circuit-breaker needs additional time upon receiving the tripping signal in order to trip and extinguish the electrical arc in the circuit-breaker.

A relay is said to ‘pickup’ when it changes from a de-energized position to an energized position. The relay pickup is the first action following the point at which a relay has registered a disturbance in the power system. Fault determination follows the relay pickup, after which commands to the circuit breakers may or may not be issued, depending on the protection zone of the relay within which a fault has occurred, as well as other parameters such are duration and type of fault. This means a relay pickup does not always result in a line tripping. A circuit-breaker command is preceded by a relay pickup, which has a much shorter time delay than the event that triggered the protection relay operation. Therefore, the relay pickup has been used to correlate time with lightning data from LLS.

A measurement of the relay pickup time has been conducted for the particular relay protection device. The testing device was used as the signal’s generator source measured at an exact point.

Both the testing device and the relay were GPS synchronized. The results of 21 measurements have shown that the pickup time of the particular relay varies from 5 ms to 28 ms after the signal generation point. The average relay pickup time value after the signal generation is measured to be 17 ms.

Therefore, it could be concluded that the lightning stroke, which excited the relay protection device, had to occur in the time range between 5 ms (minimum) and 28 ms (maximum) before the relay pickup time. Repeated tests have proven this fact to be true.

The time difference of maximum of 1 second between the relay pickup time and the time of lightning stroke recorded by LLS has been determined as the criterion for the time correlation between the fault and the lightning stroke.

A. Case Study 1

The differences between the fault detection times of a relay’s protection device (pickup 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, Figure 1. The overhead line passes through a region whose average isokeraunic value is up to 40 thunderstorm days per year, and is thereby exposed to the frequent strokes of lightning, Figure 2.

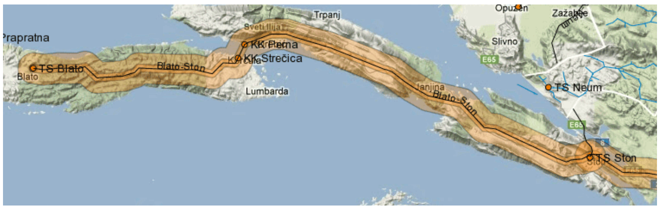

Figure 1. Monitored power line with 2 km radius alarm zones

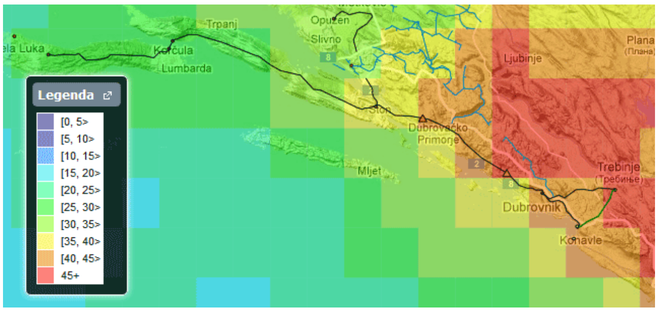

Figure 2. Isokeraunic map of the observed area

It is important to note that the relay protection devices of one overhead line can detect the fault on adjacent overhead lines within interconnected transmission network, as well. In such cases, however, the relay protection does not initiate a tripping command in the first protection zone, due to the relay protection’s zone selectivity.

During the observed three-year period 82 events registered by the relay protection devices were reported. The events for which the exact data about the relay pickup time were not available, as well as the events for which LLS did not indicate any lightning activity, were excluded from the correlation procedure. Hence, the time correlation procedure was conducted for 59 events assumed to be 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 relay pickup time and the time of the lightning stroke although there were lightning strokes in the vicinity to the observed overhead lines and in the time period close to the fault detection time. For the 53 of the analyzed events which matched the given criteria of the time difference the time correlation between the lightning strokes and the protection device fault detection was validated.

It is possible that some of the analyzed events were caused by influences other than lightning activity, e.g. strong winds. Nevertheless, the number of faults which were successfully correlated with lighting strokes in relation to the total number of faults which were assumed to be caused by the lightning activity shows the detection efficiency (DE) of the LSS of approximately 90%.

The time differences between the lightning strokes recorded by LLS and the relay pickup time for the 53 correlated and analyzed events (transmission lines faults) are shown in Figure 3.

The analysis of 53 events has been conducted separately for the 31 individual lightning strokes to the overhead line, which was the subject of the study, and for the 22 individual lightning strokes to the adjacent overhead lines. Figure 3 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.

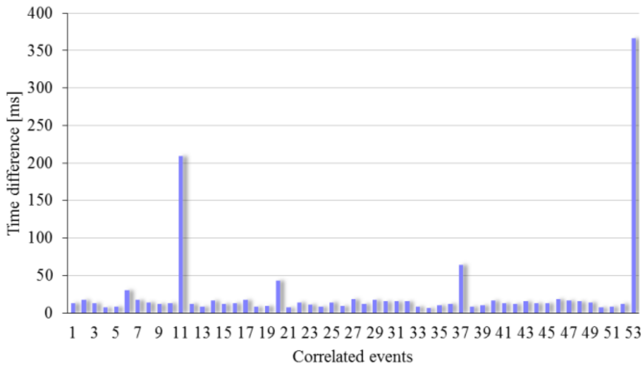

Figure 3. The correlated time difference between the lightning strokes and the protection device pickups for 53 events

The distribution of the correlated events according to time differences in the time range of 1-100 ms is illustrated in Figure 4, and Figure 5 depicts more precise 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 4) with 48 of the 53 correlated events (91%) with a time difference up to 18 ms. (Figure 5).

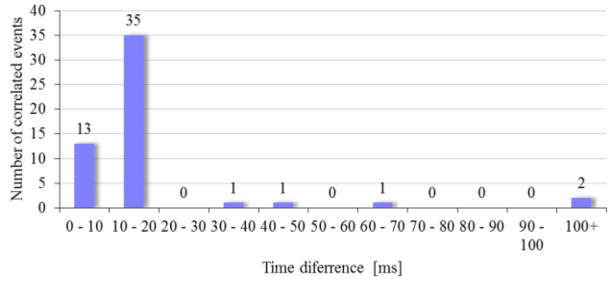

Figure 4. The distribution of correlated events according to the time differences between the time of lightning strokes and the relay protrection device pickup time

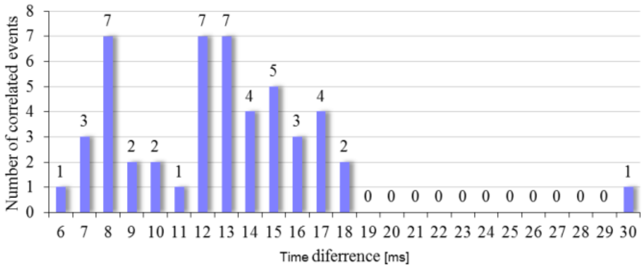

Figure 5. The distribution of correlated events according to the time differences between the lightning strokes and relay protection device pickup time

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 on the overhead lines 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 6). 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.

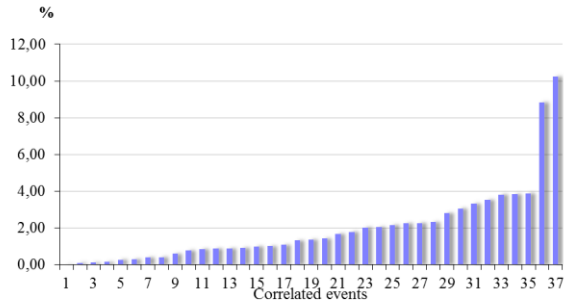

Figure 6. Differences between the lightning strokes locations determined by LLS and fault locations determined by the protection device

Although the analyses of the differences between the lightning stroke locations and fault locations has been conducted under already mentioned restrictive circumstances, the spatial correlation additionally validates the time 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.

B. Case Study 2

Relay protection data from the substation Komolac was available, hence the three 110 kV overhead power lines connected to the substation (Figure 7 and Table I) were monitored for lightning activity. The distance relays on all of the three 110 kV lines are of the same kind and type as the ones used in the previous study and in the relay pickup measurements.

Figure 7. Monitored power lines with 2 km radius alarm zones

TABLE I. MONITORED POWER LINES

Line	Voltage	Length
Ston-Komolac	110 kV	43.611 km
Komolac-Trebinje	110 kV	17.602 km
Komolac-Plat	110 kV	12.367 km

Station computer data regarding relay protection operation of the 110 kV lines were extracted for analyses. Data contain information on relay pickup, switching, fault location, etc. from January 2009 to February 2012 (38 months). The protection relays are GPS synchronized and contain a timestamp with 1 ms resolution.

To fully understand why the relay pickup signal, and not the trip signal, was used for the time correlation with lightning data, we analyzed the relay pickup to trip delay. Although the median values are in range of 10 ms, the maximum values can exceed 1 second, Table II. This is the case when the protection relay operates in the 2nd, 3rd or 5th protection zone and has a longer time delay. Also, in case of a circuit breaker dead time, the trip commands are issued with a longer time delay. For this reason, the pickup signal is a much better choice for correlation with lightning data.

TABLE II. RELAY PICKUP TO TRIP DELAY

Line	**Pickup to Trip Delay [s]**		
	Max	***Median***	***Average***
Ston	1.505	0.007	0.198
Trebinje	1.343	0.005	0.284
Plat	1.020	0.014	0.030

During the three-year period 88 events were registered by the relay protection on the observed 110 kV overhead lines. The events for which LLS did not indicate any lightning activity were excluded from the correlation procedure. Events for which exact data on relay pickup times were not available, as well as the events where relay protection was activated due to lightning influences on neighboring transmission lines are out of the scope of this survey. The time correlation procedure was conducted for 76 events registered by the relay protection on the observed 110 kV overhead lines and assumed to be caused by atmospheric discharges.

Thirteen of the analyzed faults did not match the correlation criteria and 63 of the analyzed events were correlated according to the given criteria (1 second time windows from lightning stroke to the relay pickup). The number of faults which were successfully correlated with lighting strokes in relation to all faults which were assumed to be caused by lightning activity indicates the detection efficiency (DE) of the LSS of 83% or higher. The fault assumption in relay protection reports is a subjective assessment and is subject to error.

Time correlations show a total of 63 positive correlations, with a median time delay value of 13 ms from the lightning stroke to the relay pickup. There are 38 positive correlations for the Ston-Komolac overhead line, 15 for the Komolac-Trebinje overhead line and 10 for the Komolac-Plat overhead line. The mean values of the stroke to pickup delay are 14 ms, 10 ms and 18 ms, respectively.

Statistics in Figure 8, 9 and 10 correspond to correlations between lightning strokes to the overhead line alarm zone and the relay pickups in the 1st protection zone. Further correlations are found if relay pickups (and tripping signals) are correlated with lightning strokes to surrounding overhead lines (which correspond to the relay's 2nd, 3rd and 5th protection zone), but those correlations are not the subject of this study.

Protection relay fault locator data were available for most, but not all, of the 63 analyzed correlations on monitored overhead lines in substation Komolac. Therefore, the correlation between the lightning stroke locations and the fault locator data was conducted for 56 measurements. The median location difference between the lightning stroke locations and the locations calculated by the fault locator is 1.2 km for all correlations. Median values for individual overhead lines are shown in Table III.

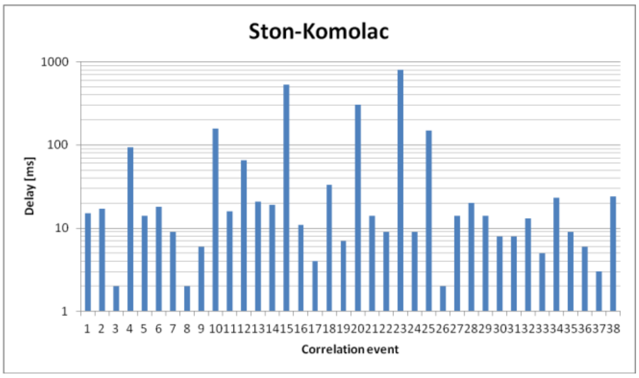

Figure 8. Lightning stroke to relay pickup delay for the Ston-Komolac overhead line

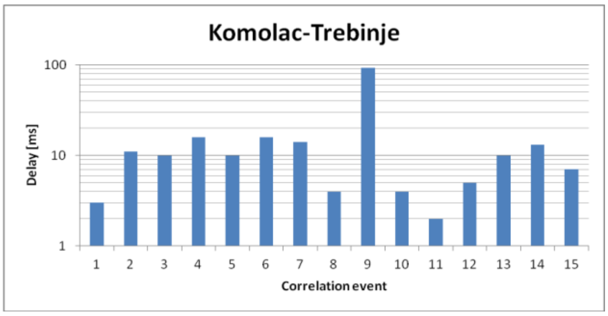

Figure 9. Lightning stroke to relay pickup delay for the Komolac-Trebinje overhead line

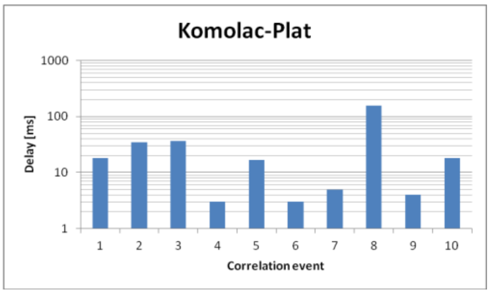

Figure 10. Lightning stroke to relay pickup delay for the Komolac-Plat overhead line

TABLE III. LOCATION DIFFERENCE

Line	**LLS to Fault Locator Difference**	
	No	***Median Location Difference [km]***
Ston-Komolac	35	1.6
Komolac-Trebinje	13	1.0
Komolac-Plat	8	0.5
Total	56	1.2

It should be noted there is a difference between the line lengths from the GIS (geometry) data and the fault locator. The fault locator line length takes into account line sags, distances from the first tower to the busbars and lengths to the measurement transformers.

IV. CONCLUSION

The time correlation between lightning strokes recorded by the LLS and line faults recorded by the relay protection has been studied during a three year period. Lightning activity around four 110 kV overhead lines has been monitored for which geographic (GIS) data and relay protection data were available. Monitored overhead lines pass through an area of heightened lightning activity.

Relay pickup delay tests show a maximum of 28 ms time delay from the induced signal to relay pickup signal. Conducted studies of correlation between relay pickups and lightning strokes indicate 85% of the correlated events with a time delay less or equal to 28 ms. The further investigation should reveal the causes of missing time correlation between relay pickups and lightning strokes.

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