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MEDIUM VOLTAGE LINE FAULT TO LIGHTNING REAL-TIME CORRELATOR

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INTRODUCTION

Deregulation of the electric energy market in countries which have decided to accept this new trading model has opened a whole new perspective regarding business responsibilities and has added a new economic weight to the quality of electric energy supply. The “quality of energy” supplied to consumers has a broader meaning which is covered by the EN 50160 standard. The major problem in meeting the required standard availability is interruptions of supply. The basic role of a public distribution network utility is a continuous supply of electric energy that meets certain quality criteria to all consumers. This means that besides standard factors (amplitude and harmonic distortion) also the lowest possible number of interruptions. However, if they occur they, should be as short as possible. Consequently, fault locations, in cases of unscheduled interruptions, should be located in shorter periods of time in order to assure faster normal operation restoration.
A significant share in unscheduled interruptions are the ones caused by atmospheric discharges which may result in permanent faults and outages. Because of the relatively low basic insulation level (BIL), almost all direct lightning strokes to the phase conductor cause flashovers and phase-to-earth short-circuits. Damaged post or string insulators are common by experienced maintenance crews repairing damages. However, fault location is usually a difficult and time-consuming task. The first reason is usually great size of the network, the second is bad weather which worseness conditions for work and the third is that the many faults are not visible from the ground level which means that maintenance crews are not able to spot the fault quickly.
The real-time fault to lightning correlator for transmission lines [1,2] offers fault location information allowing for a better coordination between the transmission system operator control center and maintenance crews. It has been in operation since the year 2000. The use of the correlator has proved to be of a great help in the lowering the time needed for fault location. The so far attained results suggest that such tool would be even more useful for the distribution network than for the transmission network, primarily for the reason of the higher number of lightning incidence on the MV level.

THE CORRELATION CONCEPT

The main tasks of Slovenian lightning localization system (LLS) SCALAR are:
1. location of atmospheric discharges and
2. dissemination of lightning information to end users [3,4,5,6].

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Besides the above SCALAR also offers new, not yet sufficiently well established but very important added value services, such as real-time correlation of overhead transmission [1,2] and distribution line faults.
When correlating outages of a power line caused by lightning strokes, one must consider correlations in the time and space domain. Both correlations must be in agreement to be sure that the line fault has really been caused by a lightning stroke.
The following are the input data (Figure 1) that should be made available for real-time correlation:

- real-time outage information from the SCADA system,
- real-time lightning information from LLS and
- geographical information from the geographical information system (GIS) which includes circuit-breakers.

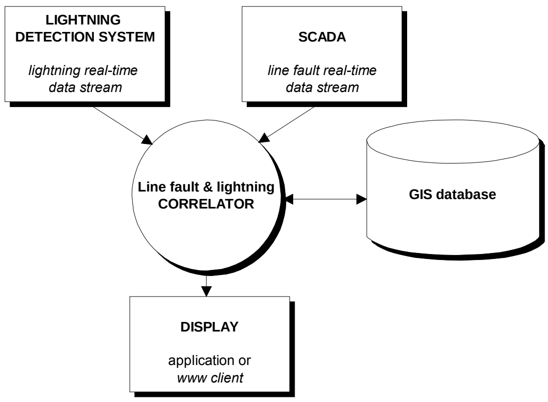

Figure 1: Basic data flow in correlation process

A multi threaded, multi user correlator *CorrelatorServer* is a JAVA application that processes information on line faults and lightning locations. Based on the topology and geography of the power line or feeder, it compares adequate data of each event in the process named correlation. The application is architectured in the way allowing correlation of not only transmission and distribution lines (400, 220, 110, 35, 20 and 10 kV) but also other installations (radio and TV transceivers, railway lines, mobile telephony base stations, etc).
As depicted in Figure 2, the *CorrelatorServer* is part of a co-operative lightning information system of the SCALAR system. The system itself is distributed and servers may run on different computers, using services provided by co-operative servers.

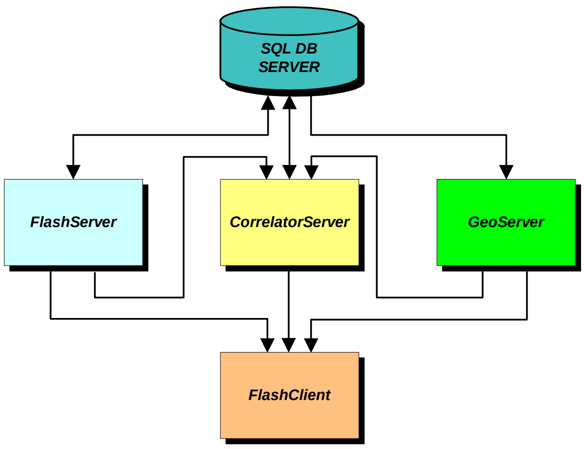

Figure 2: Communication between different programs

Together they form a robust but flexible lightning information system that provides different on-line and off-line services (statistical analyses, flash density maps, thunderstorm maps, etc).

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CORRELATION PROCESSES

The *CorrelatorServer* performs various tasks through the correlation process. They can be divided into the following phases:

- **pre-processing** of the input data needed in the correlation,
- **processing** which involves queues handling and correlation, and
- **post-processing** and distribution of the correlation results to end users.

After the input data arrive to the *CorrelatorServer* data, objects are created as shown in Table 1:

- **OOI** (Object Outage Info) object, which includes data about switched-off circuit- breaker,
- **FLASH** object which contains information about the first and subsequent return strokes (time, location, amplitude and error ellipse information [7]),
- geographical object **GEODATA** which covers information on geography (vector of identifiers of the polylines that were deenergized).

Certain basic properties of these data objects must be taken into account when making temporal and spatial correlation. The table bellow explains basic properties of the used data objects.

object name	time	location	object
FLASH	✓	✓	✗
SCADA	✓	✗	✓
GEODATA	✗	✓	✓

Table 1: Object attributes in the correlation process

From the table above it can be seen that the outage object as such does not contain any geographical information of the faulty line. However, these data are implicitly included in the GEODATA object which must be merged with OOI in order to obtain complete information on the time and spatial information of the faulty line. In a practical implementation this means that the SCADA pre-processor program Line Outage Notifier (*LON*) uses in the object tagging procedure identical geographical objects, structures and identifiers as the *CorrelatorServer.*

Circuit breaker switching-off data extraction from the SCADA system

Data extraction from the SCADA system process databases is very important because it represents one of the key source information needed in the correlation process.

Data extraction from the SCADA system consists of three steps:

1. Spontaneous or periodical data collection (depends on the SCADA system) from the process database with a custom utility program or manufacturer's utility (typically some kind of archive utility program) and piping this information over the Internet to the LON's TCP port at the processing center;
2. Object outage data information processing with *LON*, where classification and mapping are made with the help of a lookup table results in the OOI identification object.
3. Sending the OOI object to the *CorrelatorServer*.

The *LON* program is responsible for translation of different inbound outage data streams to a common OOI object understood by *CorrelatorServer*. When certain feeder is disconnected by the circuit breaker, the LON software package builds a vector of disconnected sections. For this purpose the lookup table, in which all circuit breakers are uniformly paired with corresponding feeder these sections, is used. Geographical points of these sections are not included as would be expected since in this processing phase *LON* operates only with section identifications.

It should be noted that the lookup table is now static and includes "normal operation circuit breaker and load switches position". This in turn means that it does not reflect true operating conditions. However, this imperfection is only rarely considered as a drawback in correlation as it is estimated that the network operates in 98% in a normal switching state. Considering the amount the done to have completed the project to its current state, quite an effort is yet to be made to process also the true network state in the years to come.

The next important table is the circuit-breaker table holding information on the time tolerance of the SCADA time stamp, the name of substation where the breaker is located, the feeder name and other important information.

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LON from the inbound data extracts the circuit-breaker identification and with the help of the above tables creates the data object of *OOI* type (*Object Outage Information*). Besides the time stamp, this object holds also the vector of feeder sections disconnected from the bus bars and sends the OOI object to the *CorrelatorServer.*

Lightning data retrieval from the SCALAR LLS system

The data inflow from SCALAR LLS is straightforward since it is based on an in-house developed custom protocol *FlashClient-FlashServer* (FCFS), implemented in *FlashClient* program from version 1.0 onwards. It should be emphasized that the lightning data stream includes the first and all the subsequent return strokes calculated by the location algorithm.
The *CorrelatorServer* is in this case seen from the *FlashServer* just as an ordinary client communicating over the FCFS protocol.

GIS data access

For a smooth GIS data access needed in visualization inside the *FlashClient* a dedicated geographical server *GeoServer* was developed in 2000. The main goal was to create a robust, fast and reliable way of supplying GIS data over the limited bandwidth of the Internet (working well with a 28.8 kbps modem) with a centralized access and permission administration.
In 2002 a communication module and internal data structure were rewritten for a better performance. The new approach allows the server to form data packets in sizes that are as close as possible to the MTU value (typically 1500 bytes). Since each TCP/IP packet carries also a 40 byte long header (source and destination data, various status information, etc), we decide for the 1400 byte net length. This prevents the packet from being truncated into smaller packets when the size of the original packet is greater than the MTU value and does not allow inevitably header information to present overhead in case of packets much smaller than the MTU size.
In order to achieve a most fast geographical data retrieval, special algorithms were devised and implemented on the client and server side. Their main features are as follows:

- The TCP/IP protocol is used as transport protocol;
- The protocol is compact and well optimized for different geo data transmissions;
- All geographical related menus are built from the current state of the geographical database, user's permissions and profile at the connection time;
- Once the specific geographical data are retrieved from the server, they are stored in the client's internal data structure and never requested to be reloaded from the server;
- On the user's demand, a batch data download in the background is possible;
- Retrieved geographical data are cached for further use at end of session.

Temporal Correlation

The aim of the temporal correlation is to select the best candidates for the spatial correlation among a large quantity of lightning and switching-off events and is done by comparing time stamps of lightning and switching-off events. The following two factors are the ones having the main influence on the result:

1. Allowed time tolerance defined per each circuit-breaker and
2. Accuracy of the time stamp which is critical only for switching-off events.

The allowed time tolerance is a function of the expected accuracy of the time stamps from the SCADA system and is typically in the range from few hundred milliseconds (~500 ms) up to some seconds (~10s). The source of the problem is not LLS, which provides the time accuracy better than milliseconds, but the SCADA system. Some older Remote Terminal Units (RTU) still present in some substations do not tag events with time stamps because the substation has no GPS or radio-controlled clock synchronization. The event is time-stamped at the arrival to the front-end processor (FEP) in the DCC which in turn means that the time may be quite different from the original event time.

Spatial correlation

Judging from all points of view, the spatial correlation is much more complex and demanding than the temporal because data to be processed are larger and algorithms used need more mathematical calculations.
The spatial correlation is performed only on one feeder section at a time and is repeated for all sections of the feeder.

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Figure 3 shows the entire possible error ellipse, polyline or corridor outline intersections which may occur in a correlation process.

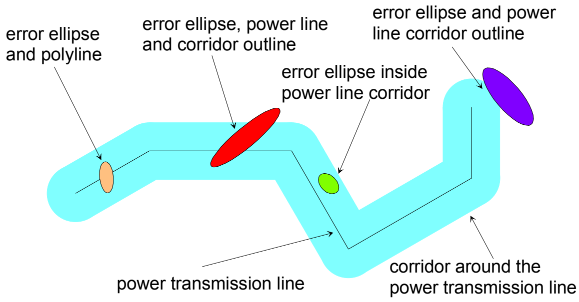

Figure 3: Possible spatial correlation cases at the line outage

Algorithms and mathematical functions used in the spatial correlation can be therefore divided into three categories:

- *Calculation of the intersection points between rotated ellipse and polyline*. The algorithm for calculation of the intersection points between an ellipse and a polyline returns the array of all possible solutions for every segment of a polyline. Mathematical functions of the algorithm are explicit and are implemented in a clear analytical way. They form the basis for further calculations (e.g. a circle is represented by a 32-element polygon).
- *Calculation of the intersection points between a rotated ellipse and a polyline corridor outline*. The power line corridor outline is calculated from polylines points in a single pass where the algorithm calculates the upper and lower outlines that are afterwards joined to form the requested polygon. The algorithm automatically adds a polyline representation of an arc between convex outline segments and cuts the outline segments at concave sections of the line. Half circles are added at the ends of the power line and serve as joining elements between the upper and lower outline.
- *Determination that an ellipse lies within a certain polygon area*. In cases when the error ellipse has no intersection point with the polyline (since it lies inside the polygon defined by an outline of the power line corridor), an algorithm for such calculation has proved to be very useful.

The typical width of the corridor is 1000 m (500 m on each side) and is related to the accuracy of the lightning location system.

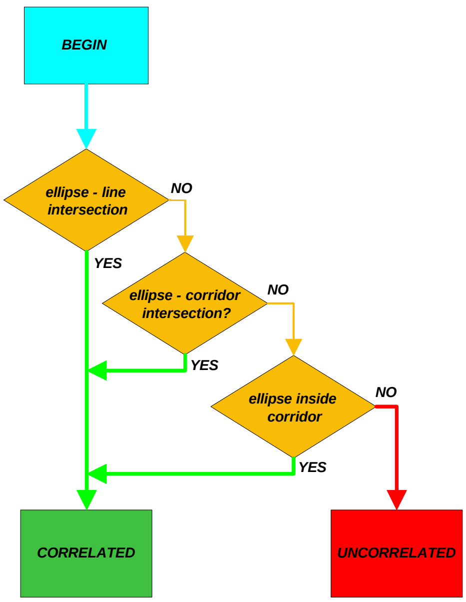

Figure 4: Possible spatial correlation cases at the line outage

The algorithm for the spatial correlation is to be as efficient and as fast as possible. It should therefore calculate intersections with the least possible effort. In Figure 4, the main steps of the spatial correlation are presented.

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All calculations are analytical and are performed in an orthogonal coordinate system. Prior to calculating, all points have to be transformed from the $\lambda\varphi$ coordinate system into the Gauss-Krüger, which is the official projection in Slovenia. Of course, after the calculation is completed, results have to be retransformed into the original coordinate system.

RESULT VISUALIZATION

For graphical visualization of correlation results the *FlashClient,* which is a multi-purpose client software is used. The main features of *FlashClient* program are:

- Real-time and historical lightning information presentation;
- Flash density and thunderstorm map creation;
- Real-time and historical correlated events presentation.

The *CorrelatorServer* and *FlashClient* use identical GIS data which minimize the amount of data to be exchanged for visualization. The data packet therefore includes only the feeder sections identification vector, time stamp of event, return stroke parameters and quality flags. Hereafter only modules and functionalities linked to the line fault correlation will be briefly explained.

Real-time operation

When the client operates in the real-time mode, it is connected to the *CorrelatorServer* real-time data stream and displays correlated events as they arrive.

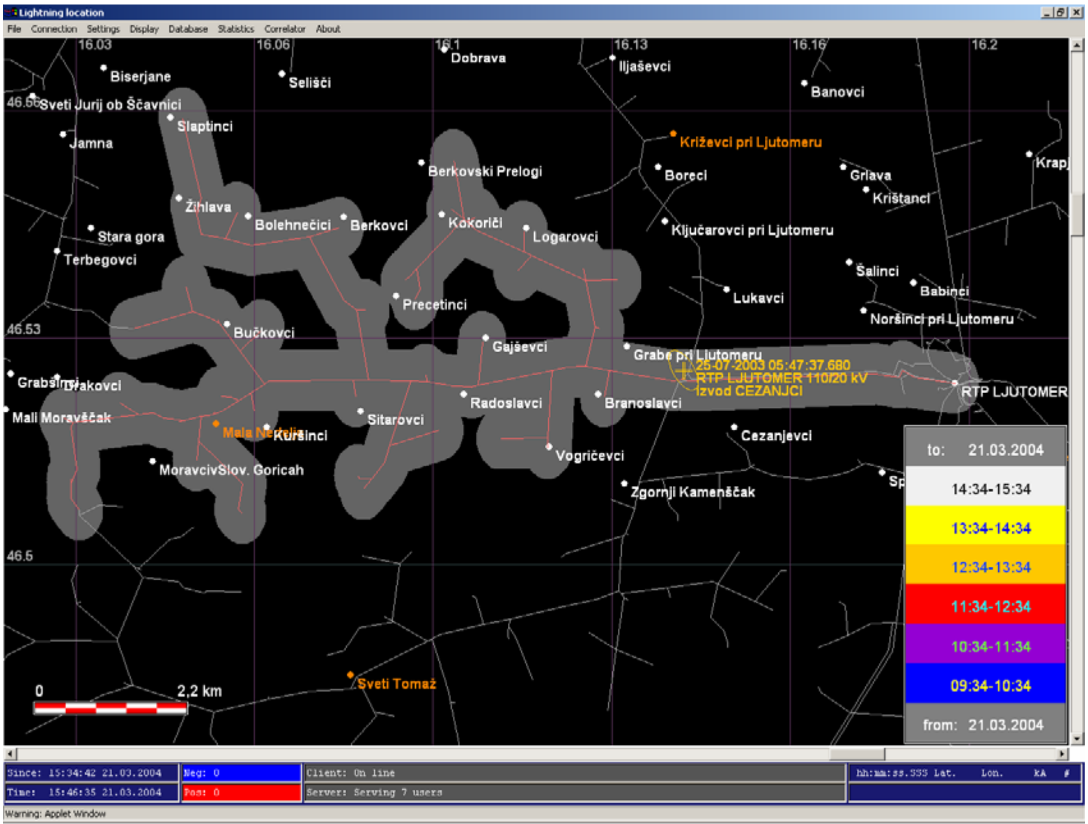

Figure 5: Correlated event of the substation Ljutomer 110/20 kV on July 26th, 2003, at 5:47:37.680.

By the default the last arrived correlated event is displayed. Each event has the following information:

- event date,
- event time with a millisecond precision,
- substation from which the feeder originates,
- name of the feeder, and
- lightning parameters.

Figure 5 shows a correlated event at the Cezanjci feeder from the Ljutomer 110/20 kV substation on July 26th, 2003, at 5:47:37.680.

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Besides the simple set of information displayed by default, more detailed information can be reached by enabling navigator window which offers graphical browsing between the events in the *FlashClient* as show in Figure 6.

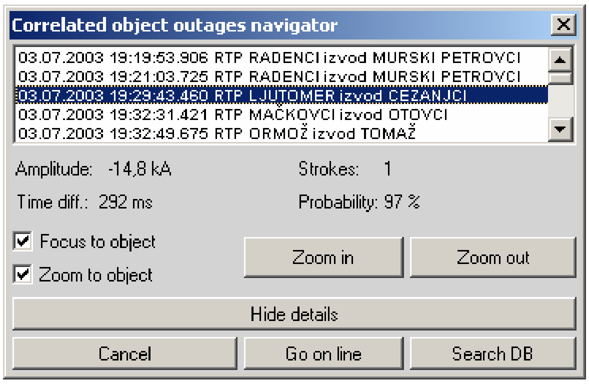

Figure 6: Navigator for a detailed exploration of a correlated event

Archived data access

The client program offers also archived data retrieval from the database which is located at the SCALAR center with the help of a graphical user interface. The interface offers data retrieval based on the time span, voltage level and of substation as seen in the figure below.

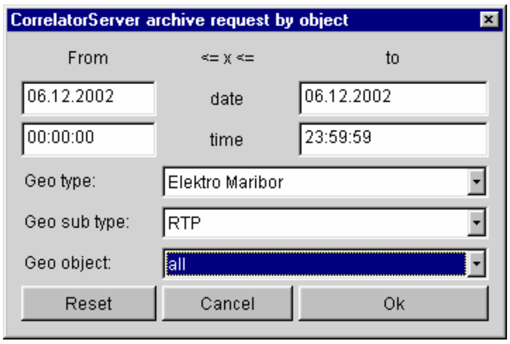

Figure 7: Dialog window for correlated events archive request

Once the requested correlated events arrive at the client they can be explored in detail with the tool described above.

Statistical access

Statistical access allows data retrieval for quick in-client statistical evaluations with the possibility of exporting all received events into the ASCII file for a further in-depth statistical analysis.

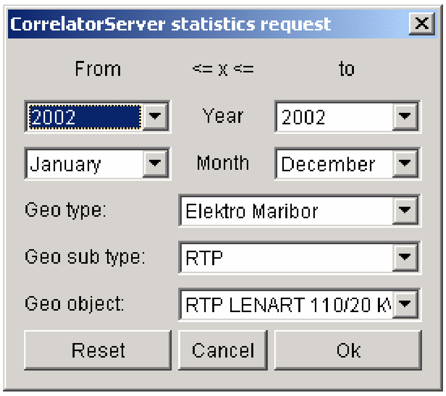

Figure 8: Dialog for a statistics request

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COLLECTED RESULTS

The correlator was officially put in operation in March 2003. Results of a one year operation show that the correlator is a good tool for localizing faults caused by lightning. "Correlator-coordinated" maintenance crews usually need only 3 to 10 or even more less time to locate the fault. These results have encouraged another four distribution utilities in Slovenia to go for implementation.
Although a one year operation is not enough for drawing representative conclusions, some information might nevertheless be of interest.

Description of the network

The distribution utility for which the correlator was implemented operates on the 20 kV level mainly in rural areas of the eastern part of Slovenia. The majority of the network, (the total length of the 20 kV feeders is 2877 km) is oh the overhead type built mostly on 10 m high poles. The total number of substations is 19, majority of them 110/20 kV. They supply 190 feeders. 120 of the 190 circuit-breakers (63 %) have their time tolerance set at 500 ms, and the test 37% with poor time stamping at 10000 ms. The area is about 4000 km^2 large.

Reclosing strategy

The reclosing time of the circuit-breakers at earth-to-ground short circuits of the distribution power utility for, which the correlator was implemented, is slow. It lasts 30 s. For this particular implementation and on customer request no distinction was made between successful slow reclosures and definitive disconnections of the feeder in the first stage. So all correlated events do not necessarily mean also actual fault. This must be kept in mind when evaluating and comparing results with other data.

Flash density

The flash density in the observed region ranges from 1 to 2 flashes/km^2/year. This density is rather low compared to the central and western part of Slovenia where it can reach values from 4 to 8 flashes/km^2/year.

Number of correlated events

In the one year operation 97 events were correlated. It should be mentioned that all thunderstorms were processed in real-time and no system malfunctioning was observed. The peak number of the correlated events was reached on July 17th, 2003, when 19 events were correlated.
The average time difference between SCADA and the return stroke time stamp very much depends on the time tolerance allowed for certain circuit-breaker. For the 500 ms tolerance margin is 242 ms and for 10000 ms this is 2992 ms.

Location accuracy

When evaluating location accuracy of the LLS through correlated events one should keep in mind that:

1. The feeder is an object built of many linear sections. This means that the location may vary from smallest lateral distance;
2. Damage caused by lightning strike may appear (especially in case of wooden towers) some kilometers away from the true lightning location.
3. During the correlation process the "best candidate" is selected among all the correlated return strokes.
4. No official feed-back information from the distribution utility is supplied on a regular basis to report on the discrepancy between the fault and lightning location.

The average semi major axis of the error ellipse is 552 m and the semi minor axis is 272 m. These are reasonable values. Evaluation of the correlated stroke locations (center of the error ellipse) show that 84 (86%) strokes lie within 500 m wide corridor and 13 (14%) outside it. This confirms our expectations that the accuracy of the system is typically bellow 500m.

Polarity and the median amplitude value

Among 97 lightning events, 91 strokes (94%) have a negative polarity and 6 (6%) a positive one. This is in good agreement with long term statistics for Slovenia (93% negative, 7% positive).

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The median absolute amplitude value of the correlated return strokes is 11.6 kA. This is slightly lower than the long-term median value for Slovenia which is 13 kA.

Flashover estimation

Based on the number of correlated events and size of the network, a rough estimation on the flashover rate of 3,37 flashovers/100km/year is obtained. If we normalize this value to the flash density of 1 flash/km^2/year value this would be 2.22 flashovers/100km/year. This value is in a good agreement with hand-made correlations made on a large dataset in the western part of Slovenia where we obtained the value of 2.37 flashovers/100km/year.

CONCLUSION

The correlator tool has exceeded all expectations and has proved that it can offer a good estimation of the true location of faults caused by lightning strokes. It is this reason that it has been quickly accepted by the distribution control center personnel.
Future improvements will include fast and slow circuit-breaker reclosure processing on per customer basis, spatial correlation for a true network switching state and some visualization improvements having been suggested by customers.
Establishing a regular feed-back information flow on true fault locations is an imperative for an in-depth evaluation of correlated events.

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