EVALUATION OF LIGHTNING THREAT IN DISTRIBUTION NETWORKS

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ABSTRACT

The paper deals with the evaluation of lightning threat to distribution network feeders based on high-resolution flash density maps.

High-resolution flash density maps with a resolution of 100 x 100 m are calculated from lightning information collected by a lightning location system. Lightning information used in a process of map calculation includes error ellipse, which is part of localization result, and is used for estimation of the location accuracy of a particular lightning event.

Phases of map calculation are described and commented. By implementation of advanced topological and spatial analysis of the distribution network, it is possible to evaluate lightning threat probability per feeder.

Feeder’s exposure may be afterwards presented with a probability curve relative to its length or with a single value as result of the momentum calculation also described in the paper. Results obtained with this evaluation are a basis for distribution line lightning protection optimization.

INTRODUCTION

Atmospheric discharges significantly influence the operation reliability of the distribution lines. The number of lightning-caused failures in power distribution networks is high primarily due to the relatively low basic insulation level (BIL). To lower the number of supply interruptions and other lightning-related disturbances, several well-known counter-measures are used: increasing the BIL, installing a ground wire, using line surge arresters (LSAs) and, as a last resort, replacing the overhead line with underground cable.

The decision which protective measure to apply should be made upon cost-benefit analysis which is based on the lightning threat.

This paper describes the procedure for assessing the lightning threat to MV network feeders based on high-resolution flash density maps (HRFD). The resolution of the map used in such analysis is 100 x 100 m, which corresponds to a typical span length for a medium voltage distribution network. HRFD maps can be used in advanced analysis, giving as a result the probability of a certain flash density along a particular feeder.

Knowing which feeders are more exposed allows for an enhanced decision making process, as it gives better insight into what the exposure of the feeder to lightning actually is. Lightning data collected with national LLS allow detailed analysis not only of flash densities but also the statistical analysis of the lightning peak currents and multiplicity of the return strokes.

Especially calculations of flash density maps based on lightning data collected on a year-by-year basis allow for assessing real lightning threat of the distribution networks. Due to the specific geographical location of Slovenia, where influences of the Mediterranean, continental and alpine climates are present and the fact that Slovenia is orographically very diverse country a clear need for a better approach in lightning exposure calculation was needed.

LIGHTNING THREAT EVALUATION

Lightning threat evaluation is performed through calculation of the flash density and statistical evaluation of parameters of lightning events for a particular region or object.

The flash density gives an average annual number of flashes per km² per year, while statistical evaluation of lightning parameters primarily deals with lightning amplitudes and return stroke multiplicity. Most common results are median value, frequency and probability distribution of amplitudes.

Simple flash density calculation

Usually the flash density is calculated that way that the geographic region in question is gridded in 1 x 1 km squares, and afterwards the number of flashes within each square are counted and divided by the number of years in which flashes were detected.

This approach is based on the following assumptions:

1. The lightning location provided by an LLS is accurate (which is not completely true, as analysis of the exposure of the line’s corridor width remains unsolved).

2. Flash density in the square in question is homogeneous (which is not completely true when the area in question is not ideally flat – all tall objects enhance the shading effect and collect more lightning).

3. A resolution of 1 x 1 km is precise enough (which is not true, as analysis of the exposure of the line’s corridor width is more than 10 times narrower).

All the above assumptions are therefore not completely true, and this calls for a novel approach which takes into account the accuracy of estimating the lightning location and the fact that the real flash density is heterogeneous, and provides higher resolution. A workaround for heterogeneous flash density is to perform the gridding with smaller squares; however, the accuracy of the lightning locations still remains unsolved.
Advanced flash density calculation

Lightning location accuracy
To improve LLS accuracy, a statistical approach is needed. A large amount of lightning data on the area of interest could give us 5 to 10 times better flash density resolution if the error ellipse method calculation is used. The statistical resolution is limited mainly due to the overall performance of the LLS. As Fig. 1 shows, the quality of LLS data is constantly improving over time, and therefore the ellipse resolution is limited mainly due to the overall performance.

A large amount of lightning data on the area of interest is needed to improve LLS accuracy. A statistical approach is essential. The error ellipse method calculation takes this into consideration.

The best obtainable LLS accuracy given by error ellipse area is defined as \( A_d(t) \), and it is a function of time (see Fig. 1). The performance of an LLS improves in steps as a result of, for example, increasing the number of sensors in the network or replacement of old sensors with newer and better ones, or by application of modifications to the lightning location algorithm. Between steps, the \( A_d(t) \) is basically constant and can be expressed as \( A_n \) for a particular time period.

\[
W_i = \begin{cases} 
1 & ; A_i < A_n \\
\frac{A_i}{A_n} & ; A_i \geq A_n 
\end{cases} \tag{1}
\]

Weight \( W_i \) is closely related to the best obtainable LLS accuracy and defines a way to translate a single flash to the ground area.

Let there be a population \( P \) of flashes from which the flash density map should be calculated and let the number of flashes be \( N \). Let the error ellipse \( e_i \), with an area \( A_n \), which is an element of \( P \) \( (e_i \in P) \) and a function of the coordinates \((\lambda, \varphi)\), semi-major \( a \) and minor axis \( b \), and ellipse inclination \( \alpha \) \( (e_i = f(\lambda, \varphi, a, b, \alpha)) \) and placed in a spherical coordinate system, be assigned an ellipse weight \( W_e \).

\[
W_e(x, y) = W_i \ast \sum_{k=1}^{M} W_{x,y} \tag{2}
\]

Weight \( W_e \) represents the weighted occurrence of one flash.

Further, let the ellipse \( A_i \) be transformed from the spherical into the Cartesian coordinate system with a reference grid. The transformation is bijective. The size of the increment in the reference grid should be at least 10 times smaller than the side of the square of the required target resolution of the map.

After transformation of a particular error ellipse \( e_i \), decomposition may start. In the decomposition phase the ellipse area in question is gridded into finite differential squares \( a_i \), for which it is true that area \( a_i \) is much smaller than the area of the original ellipse \( a_i \ll A_i \) (see Fig. 3 for details) and each of the differential squares \( a_i \) is also appropriately placed in a reference grid; thus it becomes a member of a certain reference location \( L_{x,y} \). During this phase a complete population of ellipses \( P \) is subjected to differentiating, weighting and positioning. The weight of each finite differential square \( a_i \) that is an element of \( A_i \) is \( w_n \) reciprocal to the number of squares \( k_i \) building the error ellipse.

\[
w_n = \frac{W_n}{k_i} \tag{3}
\]

And as \( W_i \) is always less than or equal to 1, we may write that \( w_i \) is:

\[
w_i \leq \frac{1}{k_i} \tag{4}
\]

This means that differential squares \( a_i \) for large error ellipses have a smaller weight \( w_n \) than those obtained from smaller ellipses.

In the next phase, composition takes place, in which the summation of the weights is performed. For each reference square \( L_{x,y} \), summation over all weights \( w_{x,y} \) is performed:

\[
W(x, y) = \sum_{j=1}^{M} w_{j,x,y} \tag{5}
\]

The final stage is normalization of the weights \( W(x,y) \) based on the size of the square and the time span for which the map is calculated.

The result of this process is a high-resolution flash density map with typical resolution of 100 x 100 m. The 100 m
finite square side dimension is a compromise between the high quantity and quality of data.

\[ \Delta x = \Delta y \]

\[ \Delta X \]

Legend:

- weight \( w_1 \)
- weight \( w_2 \)
- weight \( w_3 \)

\[ \text{ellipse } e_1 \]

\[ \text{ellipse } e_2 \]

\[ \text{ellipse } e_3 \]

**Topology calculation**

In order to evaluate a threat, we must first identify the zone the feeder is supplying power to. We do this by using the network topology processor (NTP). NTP was developed as part of automatic fault localization based on lightning data [4], but also proved to be useful in the case of lightning threat evaluation. Its purpose is to calculate the set of sections which comprise the particular feeder.

**Spatial calculations**

After the set of sections has been calculated, the geography of the power lines is retrieved from a GIS-enabled database and layered on the top of flash density map data, which also resides in the aforementioned GIS database. Then, calculation of the length of intersections between the power lines' geographies and the geographies of flash density in 100 x 100 m squares takes place.

**Probability calculations**

The lengths of intersections are next grouped according to the \( N_g \) of the squares crossed by the power lines. Then the lengths of intersections in each group are summed and the groups are ordered by \( N_g \) from zero to the maximum \( N_g \) value observed in the area the power lines cross. The result of this is a distribution curve that tells us how much of the feeder-protected area overlaps an area with a given flash density value.

If investigated further, a normalized cumulative distribution curve can be generated. From this curve one can see what portion of the power lines is under a higher threat than the chosen \( N_g \). Fig. 5 shows the cumulative distribution curve for all the feeders of a substation.

In Fig. 5, one can see that 10% of sections of all feeders lie on an area where \( N_g \) is greater than 5. It can also be observed that the most exposed feeder is Anhovo II, which has 50% percent of its sections exposed to an \( N_g \) of more than 5.3 flashes/km²/year.

Fig. 10 shows a graphic representation of the flash density along the Dobrovo feeder of the Plave substation. As one can see from the legend, this particular feeder crosses a region where the flash density varies from 0.8 (white) up to 6.6 flashes/km²/year (dark blue). Using this graphic presentation, hotspots in distribution networks are easily determined and proper action may be taken.

It should be noted that only the lengths of overhead lines are included in the calculation. Here, cable lines are regarded as being resistant to lightning flash strikes.
Aggregate threat calculation

Probability curves as such are valuable in assessing what portion of a feeder is exposed to a certain flash density and for comparison how feeders from certain substation are exposed, however for a distribution utility management this information is not enough. The main reason is that these results do not give information for which the protective measure should be applied first. The idea is to improve the overall network operational reliability; therefore fixing relatively most exposed feeder may not result in substantial decrease of failures.

For example, if a utility has a short feeder over high flash density region then this feeder faces lower total number of lightning caused failures as long feeder over medium flash density region. For this reason we decided to use a momentum calculation. The idea is that for every section of the feeder the finite differential momentum which is a product of an intersection length $d_{ij}$ of the section and the value of the flash density $N_{g(i,j)}$ is calculated and then finally all momentums are summed (see Fig. 8).

![Fig. 8. Illustration of aggregate threat calculation](image)

The aggregate threat $T_f$ for a particular feeder $f$ can be calculated according to Fig. 7. as:

$$T_f = \sum_{k=1}^{N} N_{g(k,i,j)}d_{k(i,j)}$$  \hspace{1cm} (6)

where $k$ is a finite square, and $N$ is the total number of finite squares crossed by the feeder. Case results are presented in table 1. If aggregate results are compared with the probability curves from Fig. 5 it can be seen that the order of relative and aggregate threats per feeder do not match.

<table>
<thead>
<tr>
<th>Feeder name</th>
<th>length [km]</th>
<th>Aggregate threat $T_f$ [flashes/km²/year]</th>
<th>$N_f$ [flashes/km²/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>maximal</td>
<td>average</td>
</tr>
<tr>
<td>Anhovo II</td>
<td>56.94</td>
<td>300.97</td>
<td>14.00</td>
</tr>
<tr>
<td>Dobrovo</td>
<td>55.60</td>
<td>277.10</td>
<td>11.70</td>
</tr>
<tr>
<td>Brda</td>
<td>20.38</td>
<td>112.18</td>
<td>11.70</td>
</tr>
<tr>
<td>Doblar</td>
<td>15.78</td>
<td>68.39</td>
<td>14.00</td>
</tr>
<tr>
<td>Mrzlek</td>
<td>10.89</td>
<td>50.36</td>
<td>9.60</td>
</tr>
<tr>
<td>Anhovo</td>
<td>3.29</td>
<td>13.92</td>
<td>8.40</td>
</tr>
</tbody>
</table>

Table 1. Results of aggregate calculation

CONCLUSION

Lightning location systems currently in use, in addition to information on the location and peak current of a lightning event, offer also information on expected errors of this event. This information is represented with an error ellipse, which may be used in the calculation of high-resolution flash density maps.

High-resolution flash density maps are useful for locating hot spots or the most exposed sections of the line, and represent good added value information to the average flash density of the power line corridor.

When the lightning threat is evaluated for medium-voltage networks, it is evident that the calculation of the probability and aggregate exposure to lightning per feeder offers valuable input data in the cost-benefit decision making process.

REFERENCES