A NOVEL METHOD FOR COST-BENEFIT EVALUATION OF LIGHTNING PROTECTION IN DISTRIBUTION NETWORKS USING FLASH DENSITY MOMENTS

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Abstract: The paper deals with the evaluation of lightning threat to distribution network feeders based on the advanced use of 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. By implementing advanced topological and spatial analysis of the distribution network, it is possible to evaluate lightning threat probability per feeder. The results of such analysis represent key input data for protective measures to undertake, such as installing line surge arresters or replacing the overhead line with a cable line. The paper also describes the procedure for determining optimal investment in line surge arresters for improving distribution line lightning performance. The procedure uses a method based on flash density moments to evaluate the impact of flash density and length of line sections to line performance and thus the cost of line failures.

1 INTRODUCTION

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 on which measure to apply should be based on operational records and information on the lightning threat of the line. This paper describes the procedure for classifying the lightning threat to MV network feeders based on high-resolution flash density maps (HRFD) with a resolution of 100 x 100 m. 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.

The use of HRFD maps enables power utilities to lower the number of interruptions by applying measures on the most exposed sections of the feeder, i.e. where the flash density is highest. Using this inventive approach, one can achieve better feeder performance with minimal investment.

2 FLASH DENSITY CALCULATION

The first lightning localization systems (LLS) were introduced some 30 years ago and gained widespread implementation by the end of the 20th century. After some years of operation, many countries began calculating flash density maps, which primarily replaced the thunderstorm-day maps ordinarily produced by national weather services. With sensor and location algorithm improvements, better and better localization efficiency was available, which in turn resulted in wider use of flash density maps in insulation coordination.

With evolving spatial analysis tools, transmission and distribution lines became the subject of fine-grained analysis. These analyses allow better insight into the real lightning threat to which lines are exposed.

A conventional way of determining flash density calculation is to grid a geographical area in 1 x 1 km squares. Then the number of flashes within each square is counted a divided by the number of years over which these flashes were detected.

Better results are achieved using the finite differential error ellipse method calculation.

2.1 Finite differential error ellipse method calculation

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.

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_i, which is an element of P ($e_i \in$ P) and a function of the coordinates (λ, φ), semi-major a and minor axis b, and ellipse inclination α ($e_i = f(\lambda, \varphi, a, b, \alpha)$) and placed in a spherical coordinate system, be assigned an ellipse weight W_i.

$$W_n(x,y) = W_i * \sum_{k=1}^{M} w_{x,y} \qquad (1)$$

Weight W_n represents the weighted occurrence of one flash.

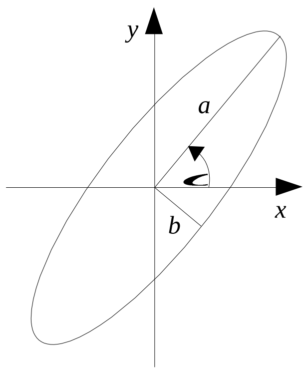

Figure 1: Error ellipse with semi-major axis and inclination angle

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 $a_i << A_i$ (see Figure 2 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.

$$w_n = \frac{W_n}{k_i} \qquad (2)$$

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

$$w_i \le \frac{1}{k_i} \qquad (3)$$

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_{jxy} is performed:

$$W(x,y) = \sum_{j=1}^{M} w_{j,x,y} \qquad (4)$$

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

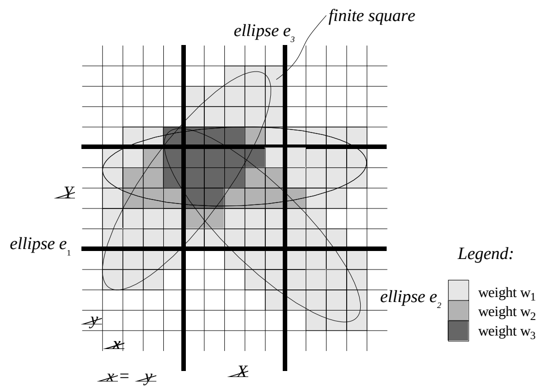

Figure 2: Error ellipse decomposition and weight summing

3 LIGHTNING THREAT EVALUATION

3.1 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.

3.2 Spatial calculations

After the set of sections has been calculated, the geography of the power lines is retrieved from a GIS-enabled database and placed on 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.

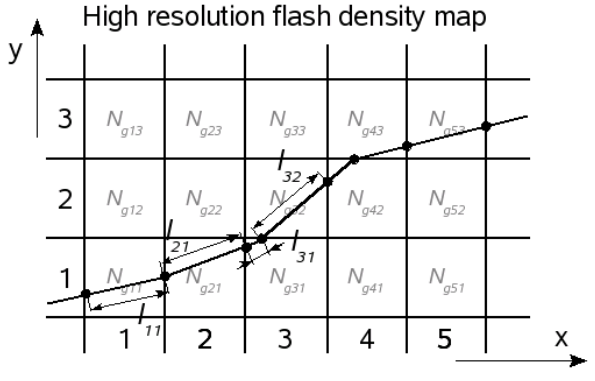

Figure 3: Moments of section length and flash density

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.

3.3 Lightning threat 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. Fiure. 5 shows the cumulative distribution curve for all the feeders of a substation.

In Figure 5, it can be observed 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/km^2/year.

Figure 6 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/km^2/year (dark blue). Using this graphic presentation, hotspots in distribution networks are easily determined and proper action may be taken.

However, in the case of the Ilirska Bistrica substation, all the feeders are less exposed than in the case of the Plave substation.

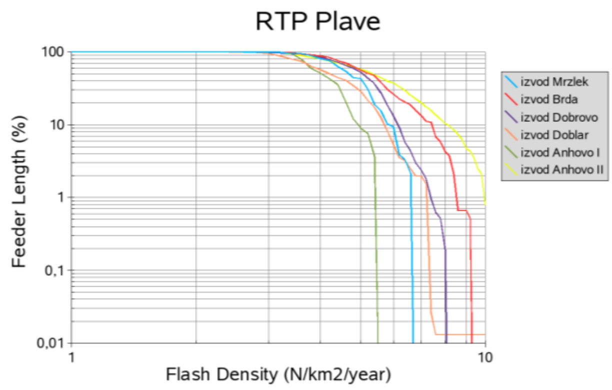

Figure 4: Flash density probability curves for Plave substation feeders

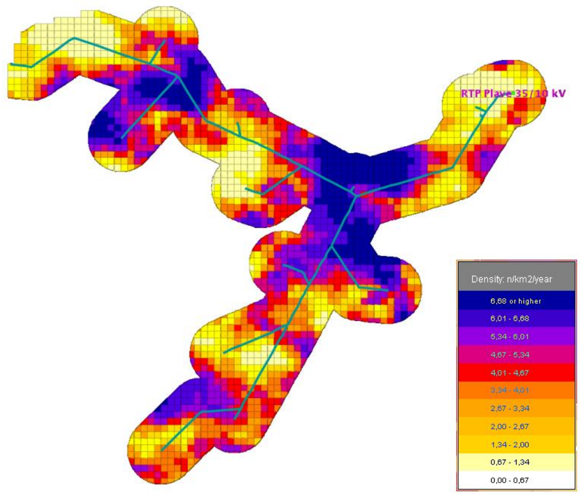

Figure 5: High resolution flash density map for the Dobrovo feeder – Plave substation

It may be quickly realized that the Ilirska Bistrica substation on average supplies the region with lower flash density, which is seen as a left-shifted probability.

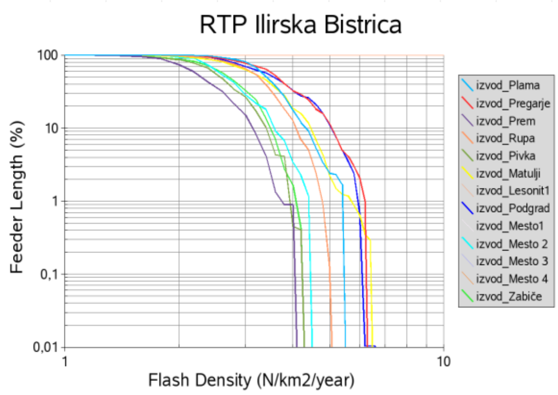

Figure 6: Flash density probability curves for Ilirska Bistrica substation feeders

In order to assess lightning threat even better we seek a better measure. The emphasis should be on the total number of failures for a distribution utility. This means that the number of failures is higher when flash density is higher and when the grid spans larger areas.

Let there be an overhead line that runs over an area with a uniform flash density N_g. We assume the differentially small failure probability d*o* on a differentially small length of the overhead line d*l* is:

$$\mathrm{d}o = k(H, U_m, R_{oz}) N_g \, \mathrm{d}l \quad (5)$$

If we knew the analytical function of N_g, we could integrate the $N_g(x)$ over the whole overhead line length and attain the aggregate feeder threat. Since this function is not known, we simplify the problem to summation of moments, represented by the product of length $l_{(i,j)}$ and flash density $N_{g(i,j)}$ in a grid cell (i,j) (See Figure 4).

For the purpose of an exemplification let us assume that variables, that define the value of *k* along the feeder, are constant and so is *k*. We are then left with the summation of the moments along the feeder:

$$o = k(H, U_m, R_{oz}) \sum_i N_{g\_i} \, \mathrm{d}x_i \quad (6)$$

Table 1: Calculated sum of moments and other characteristic values of feeder '*Plave*'

Feeder	**Feeder length (km)**	**$\sum N_g$*dl**	**Max N_g value**	**Average N_g value**	**Mean N_g value**
Mrzlek	10,9	50,4	9,6	5,2	4,7
Brda	20,4	112,2	11,7	5,6	5,2
Dobrovo	55,6	277,1	11,7	5,4	5,1
Doblar	15,8	68,4	14,0	6,0	4,2
Anhovo I	3,3	13,9	8,4	4,9	4,0
Anhovo II	57,0	301,0	14,0	5,8	5,3

From Table 1 one can see that feeders 'Anhovo II' and 'Dobrovo' are the most stressed. On this feeders we can expect twice as many failures due to lightning flashes than on the other feeders.

After ordering the sums of moments from highest to lowest and analyzing them, we could determine the set of feeders that need relatively higher investments in order to protect them from lightning flash induced failures.

Comparison sums of moments for feeders of substation 'Plave' and 'Ilirska Bistrica' to their probability distributions indicates that higher sum of moments value corresponds to a probability distribution moved to the right.

Table 2: Calculated sum of moments and other characteristic values of feeder '*Ilirska Bistrica*'

Feeder	**Feeder length (km)**	**$\sum N_g$*dl**	**Max N_g value**	**Average N_g value**	**Mean N_g value**
Plama	11,1	37,1	7,1	3,5	3,4
Pregarje	26,8	102,8	7,2	3,5	3,6
Prem	12,1	28,8	4,7	2,7	2,3
Rupa	17,4	57,0	5,9	3,4	3,3
Pivka	13,5	36,2	6,5	3,0	2,8
Matulji	40,1	126,0	8,1	3,6	3,3
Lesonit 1	1,9	0,0	4,0	3,3	0,0
Podgrad	19,6	73,7	7,2	3,7	3,6
Mesto 1	2,5	0,0	4,6	3,0	0,0
Mesto 2	12,5	24,5	6,1	3,1	2, 7
Mesto 3	4,0	0,0	4,6	3,1	0,0
Mesto 4	3,5	0,0	5,0	3,4	0,0
Zabiče	18,6	51,1	7,8	3,4	2,7

4 ECONOMIC EVALUATION

Once the high-resolution flash density probability curves for different feeders are known, an economic evaluation may be performed. The aim is to determine what the optimal investment would be in a particular feeder from the point of view of improving the line's lightning performance.

It should be emphasized that there are various measures that could be taken, including installation of line surge arresters, installation of ground wire, cabling the line, etc. Each of these measures improves the line's lightning performance, but also involves certain costs, which differ from the point of view of effectiveness and investment needed.

The task may therefore be described as seeking a solution that would either be the most economical or that would make a substantial improvement in meeting a certain predefined level of lightning performance. To complete this task, one must first calculate failures of the line if no protective measures are taken.

4.1 Assessment of the number of failures

Failure rate assessment may be performed in two ways. The first approach is to collect records of feeder failures from the operational diaries. The second approach is more analytical and is based on the findings found in [2].

The failure rate due to a direct strike to a distribution line may be written as:

$$n_f = N_g L \frac{b + 28H^{0.6}}{1000} \left[failures/year \right] \qquad (7)$$

where N_g [flashes/km^2/year] is the average flash density along the line, L [km] the total length of the feeder in km, b [m] the width of the tower head in meters, and H [m] its height.

However, as one can see from Figure 8, flash density is not homogeneous along the section of the feeder, but varies greatly mainly due to the orography of the corridors.

If we arrange flash density by value, we get the ordered flash density for a particular feeder. See figure 9.

For clarity of evaluation, let us assume that flash density is an analytical function. Then the number of failures may be expressed as a function of measured flash density n_g as the integral of infinitesimal sections of the feeder:

$$n_f(n_g) = \frac{b + 28H^{0.6}}{10} \int_0^L n_g \, dl \qquad (8)$$

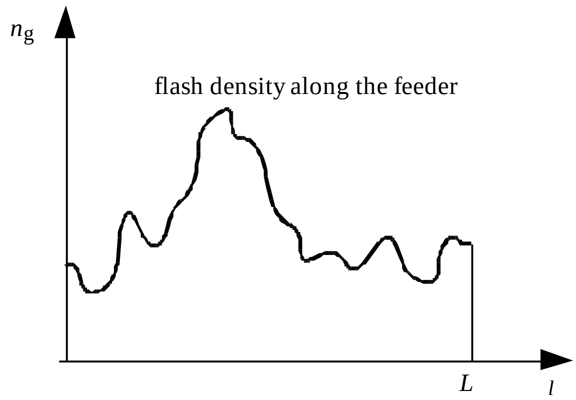

Figure 7: Actual flash density along the feeder

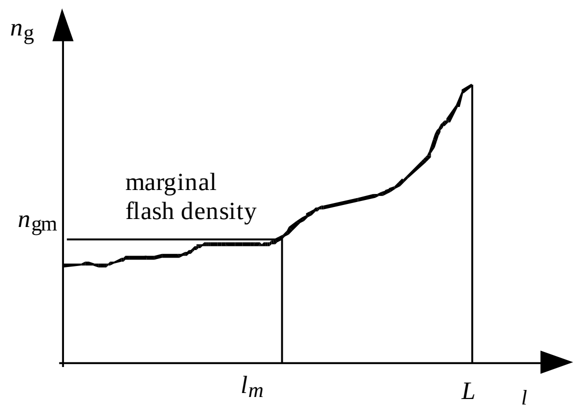

Figure 8: Ordered flash density by value

If a feeder lightning protection measure along the entire length of the feeder is introduced, the number of failures decreases by a certain factor k_d, which is less than 1 and can be written as:

$$n_f(n_g) = k_d \frac{b + 28H^{0.6}}{10} \int_0^L n_g \, dl \qquad (9)$$

On the other hand, if the protective measure is introduced only at the most exposed sections of the feeder, the number of failures takes a more general form in which we sum the number of failures at unprotected and protected lengths. The margin may be some marginal flash density n_{gm} by which one decides based on the ordered flash density function as seen in Figure 9. If this is the case, then the number of failures may be written as:

$$n_f(n_{gm}) = \frac{b + 28H^{0.6}}{10} \left(\int_0^{l_m} n_g \, dl + k_d \int_{lm}^{L} n_g \, dl \right). \qquad (10)$$

At this very point the change of the integral to the sum of differential lengths and flash density value products should be made, as ordered flash density is available as the vector of discrete values. Thus the equation takes on it final programming-ready form:

$$n_f(n_{gm}) = \frac{b + 28H^{0.6}}{10} \left(\sum_{i=0}^{l_m} n_{gi} \Delta l_i + k_d \sum_{i=l_m+1}^{L} n_g i \Delta l_i \right) \qquad (11)$$

4.2 Assessment of costs involved

Assessment of costs should take into account costs of interruptions to consumers and costs for protective measures applied. Costs of interruptions depend on the number of interruptions, duration of failures and power. Both the duration and the number of failures must be considered. For example, if we consider only the duration of the failures, the costs of short interruptions would be incorrectly insignificant. Costs of interruptions (C_i) are therefore calculated using Equation 12, where n symbolizes the number of outages, P stands for average power (kW) of the line, C_p for the cost of interrupted power (€/kW), t the total time of all outages (h) and C_e the cost of unsupplied energy (€/kWh).

$$C_i = n * P * C_p + P * t * C_e \qquad (12)$$

Let us assume that C_p and C_e are known and that the costs of protective measures taken are known and are proportional to the length protected. Then one may, based on Equation (11), write a cost function for unprotected sections of the feeder up to marginal flash density n_{gm}. Only interruption costs $c_{0,lm}$ are included in this section. Costs in protected sections include costs of reduced undelivered energy and costs of protective measures applied $c_{lm,L}$. Thus, the total cost may be expressed as:

$$c(n_{gm}) = c_{0lm} + c_{lmL}$$

$$c(n_{gm}) = c_{undelivered}(0, l_m) + c_{undelivered}(l_m, L) + c_{protection}(l_m, L) \quad (13)$$

$$c(n_{gm}) = \frac{b + 28H^{0.6}}{10} c_{un} \left(\sum_{i=0}^{l_m} n_{gi} \Delta l_i + k_d \sum_{i=l_m+1}^{L} n_g i \Delta l_i \right) + c_{pr}(L - l_m) \quad (14)$$

where c_{un} are average costs per failure [€/failure] and c_{pr} [€/km] are costs for protection per length. The optimum investment in protection is given at the point where the costs are minimal, as can be seen from Figure 10.

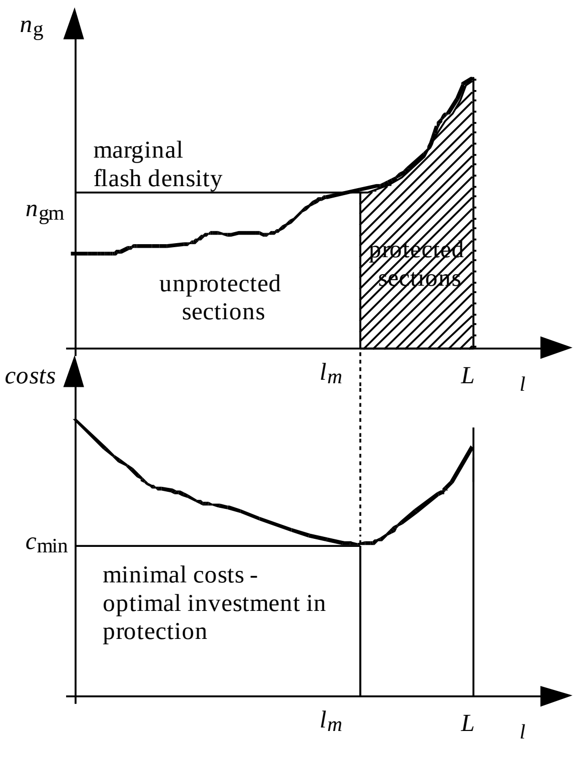

Figure 9: Cost curve with optimal investment costs

It should be noted that the optimum investment very much depends on the cost estimates used in the evaluation. If costs of purchasing and installing line surge arresters are well defined and total ~700 € per tower, then costs for undelivered energy are much more difficult to assess. First, the value of the energy constitutes only a minor part of the interruption costs. The major share of total cost is related to the inability to perform the planned activities. There is a problem in how to evaluate those costs. There are numerous methods for interruption cost assessment, which can roughly be categorized into three groups:

- indirect, analytical methods
- studies of specific outages
- direct customer questionnaires

Second, the costs of interruptions vary greatly between different customer groups. Interruption costs to residential customers are usually evaluated many times lower than industry or trade and services. Therefore, interruption costs can vary greatly from one line to another, depending on customer structure.
Finally, we have to bear in mind the difference between macroeconomic costs of interruptions and costs of interruptions that are actually paid by the utility. Every outage involves costs to customers, but only some of them are actually paid by the utility. So we need to decide whether we will consider all macroeconomic costs or just actual microeconomic costs of the utility.

There is a great variation in interruption cost assessment between different countries. For example, in Scandinavian countries the unsupplied energy cost is evaluated between 1 €/kWh and 13 €/kWh depending on the customer group, while the interrupted power cost is evaluated from 0.3 to 3.5 €/kW [5]. The Italian regulator, on the other hand, uses a fixed estimate of 15 €/kWh for unsupplied energy and 10 €/kW for interrupted power.

There are no recent studies in Slovenia on the costs of interruptions, as there have only been a few claims in practice. Only a rough assessment from the year 2000 exists, in which the unsupplied energy costs are 0.5 €/kWh and interrupted power costs 0.25 €/kW [3]. However, this estimate does not include all costs.

5 CONCLUSION

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

High-resolution flash density maps prove to be very 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 of exposure to lightning per feeder offers valuable input data in the cost-benefit decision making process. To a great extent, the results obtained using this approach help to classify feeders that operate in areas of higher or lower exposure levels as well as in determining the optimal investment in LSAs for cost-effective improvement of feeder lightning performance.

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