On the Use of Lightning Location System Data to Evaluate the Lightning Performance of Overhead Distribution Lines

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Abstract

This contribution discusses the impact of using parameters and statistical distributions derived from Lightning Location System (LLS) data on assessing the Lightning Performance (LP) of an overhead distribution line. Both negative and positive return strokes are considered in the analysis, and multiple-stroke flashes are simulated using the probability distributions for the flash multiplicity and the spatial separation of ground terminations.The LP of the same benchmark (Italian) network obtained with conventional lightning parameters available in the literature is compared with that using LLS-inferred distributions for Italy. Results reveal considerable differences in the expected number of annual flash-overs.

1 Introduction

Faults caused by lightning strikes have a major impact on power systems. Extensive research has explored how lightning discharges affect electrical infrastructure, typically discriminating between direct and indirect effects. Overhead Medium-Voltage (MV) lines are characterized by a reduced Critical Flash-Over (CFO) voltage; thus, are more vulnerable to lightning than HV transmission networks. Direct strikes on MV lines may produce more disruptive effects than indirect lightning strikes; however, the latter has a higher occurrence and tends to be the main cause of failure. At a computational level, direct strikes are much less challenging than indirect strikes because these require dedicated numerical simulations to evaluate the lightning electromagnetic fields in free space and assess the field-to-line coupling to obtain the lightning-induced overvoltages.

The evaluation of the impact of both direct and indirect lightning strikes on MV systems is commonly done through the assessment of the Lightning Performance (LP) [1], a procedure in which a large number N (e.g., 10^4) of random lightning flashes are simulated (Monte Carlo method) and the expected number of flash-overs F per year is evaluated as

$$F = 2\,\frac{n_d + n_i}{N} A N_g \tag{1}$$

where n_d (n_i) is the number of direct (indirect) strikes resulting in an overvoltage larger than the line CFO increased by 50%, as indicated in [1], A (km^2) is the simulation domain, N_g (flashes km^{-2} yr^{-1}) is the Ground Flash Density (GFD), and 2 is a factor due to symmetry.

An accurate and computationally feasible LP assessment is crucial for lightning protection of power systems. Enhancements to such a procedure have been provided by numerous contributions aimed at investigating complex networks and at studying the effects of optimal placement of protection devices (e.g., [2]) or at developing methods for reducing computational burdens (e.g., [3, 4, 5, 6, 7]). Despite its widespread application, the conventional LP assessment presents two key limitations.

1. Typically, it considers only negative first return strokes, disregarding subsequent negative and positive return strokes or addressing them partially [8, 9, 10], although the effects produced by multiple-stroke flashes may be significant.
2. The PDFs of lightning parameters are often derived from direct tower measurements, overlooking regional variations and tower-presence biases.

Addressing the first limitation, the authors of [11] presented an LP assessment approach including supplemental lightning parameters, i.e., the peak current of negative first, negative subsequent and positive return strokes, the flash multiplicity, and the distance between ground terminations.

The second limitation is given by the fact that direct tower measurements of lightning current are accurate, but limited to a few particular regions (e.g., [12, 13, 14]) and accounting for a reduced number of samples; in addition, the presence of the tower itself with its height creates a different mixture of lightning kind and form (high percentage of upward, different peak current and multiplicity) [15, 16]. On the orher hand, Lightning Location Systems (LLSs) globally record a huge amount of lightning data using electric and/or magnetic field measurements. This feature makes LLS data the optimum choice for the GFD estimation [1] and an interesting source for local and updated PDF of lightning parameters; however, the field-

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to-current linear model, integrated into the lightning location algorithm to consider field attenuation, has been validated (through rocket-triggered lightning and direct tower measurements) only for negative subsequent return strokes with peak currents lower than 60 kA [16, 17]. Moreover, LLSs typically lack front duration data.

This contribution aims at evaluating the LP of a realistic overhead MV line in Italy, considering various return stroke types with multiple ground terminations and accounting for local lightning parameters.

To address the first limitation of the conventional LP assessment, the approach proposed in [11] is applied. Local lightning parameter PDFs are adopted from a 10-year analysis of data provided by the Italian LLS *Sistema Italiano Rilevamento Fulmini* (SIRF) [18]. To consider the mentioned limits of LLSs in lightning current parameters, front duration PDFs for all return stroke types and peak current PDFs for negative first and positive return strokes are sourced from the instrumented tower measurements of Monte San Salvatore [12]. LP evaluations are performed using the method presented in [5] to ensure manageable computational efforts.

The paper structure is the following. Section 2 presents the methodology for the LP assessment. Section 3 presents the test line model and lightning parameter distributions from [18] compared to conventional literature assumptions. Section 4 presents the considered test cases, results and discussion. Finally, the paper ends with Section 5 in which concluding remarks are presented.

2 Method

2.1 Striking Area Definition

Assuming a 2-D Cartesian reference frame where the line length is L and the line ends are at positions $(0,0)$ and $(L,0)$, the striking domain where lightning flashes are simulated is $A = [x_{\min}, x_{\max}] \times [y_{\min}, y_{\max}]$. The limits on the x-axis are set at $x_{\min} = -0.5L$ and $x_{\max} = 1.5L$ (in accordance with [2, 3, 9]). As will be detailed later, the limits on the y-axis depend on the peak current distributions, thus they should change with the return stroke type. However, a unique simulation domain is selected for all simulations by considering the worst conditions (i.e., the larger area) according to what follows.

1. $y_{\max}$ is the largest distance above which any stroke induces a non-dangerous overvoltage on the line (i.e., lower than $V_{\max} = 1.5$ CFO). From the Rusck-Darveniza formula [19], that gives a conservative approximation of the induced overvoltage as a function of the distance from the line and the peak current, it is possible to obtain

$$y_{\max} = \frac{38.8}{V_{\max}} \left(h + \frac{0.15}{\sqrt{\sigma_g}} \right) I_{\max} \tag{2}$$

   where h is the line height above ground, σ_g is the ground conductivity and $I_{\max}$ is such that the probability $P(I > I_{\max})$ is reasonably close to zero.

2. $y_{\min}$ is the distance under which any lightning event results in a direct strike of the line. A peak current $I_{\min}$ such that the probability $P(I < I_{\min})$ approaches zero is selected and used in to calculate $y_{\min}$ by using the Electro-Geometric-Model (EGM) proposed in [20] and recommended in [1] .

2.2 Monte Carlo Procedure

The assessment of the LP is done following the apporach proposed in [11], taking into account different return stroke types and multiple ground terminations. Each lightning parameter (channel-base peak current I, current front duration τ_d, flash multiplicity, and distance between ground terminations) is extracted using the assumed Probability Density Function (PDF). To reduce the computational effort, such an approach exploits the method of [5] through which it is possible to obtain analytical expressions providing the maximum induced overvoltage from the coordinates of stroke location, τ_d, and I. Positive flashes are less complex to manage since positive subsequent strokes are disregarded (the positive flash multiplicity is supposed to marginally exceed one [21]).

Each flash is simulated as a sequence of strokes. If one of the strokes leads to a direct strike, the counter n_d is increased by one unit and the simulation moves to the next flash. Otherwise, the maximum stroke-induced voltage within the flash is compared to the line CFO (increased by 50%) to check the occurrence of an indirect strikes and, if so, increase the counter n_i by one unit.

As indicated in [10], flash polarity can be considered in the LP assessment with two distinct Monte Carlo procedures, one with all negative random flashes, the other with all positive random flashes. The expected number of negative (positive) flash-overs per year is labeled F_n (F_p). Then, from the law of total probability:

$$F = a_n F_n + a_p F_p \tag{3}$$

in which a_n (a_p) is a coefficient expressing the probability that a lightning flash is negative (positive) and $a_n + a_p = 1$.

3 Computational Parameters

3.1 MV Network

A 15-kV overhead distribution line with three parallel conductors of height $h = 8.0$ m for the lateral branches and $h = 8.6$ m for the central feeder is considered. Specifications are outlined in the following. Line length: $L = 1$ km, distance between conductors: 1.2 m, conductors diameter: 0.64 cm. The ground around the line is assumed with conductivity $\sigma_g = 1$ mS/m and relative permittivity $\varepsilon_g = 10$. The induced overvoltages along the test line are affected by the specific grid attributes. In this scenario, the distribution network proposed in [9] and illustrated in Figure 1 is considered. All transformers are protected by surge arresters. The primary winding of the HV/MV transformer (T_0) is connected to a 132-kV ideal voltage source modeling the main grid. Two 300-m long lateral branches are placed at distances of 250 m and 750 m from T_0 and feed

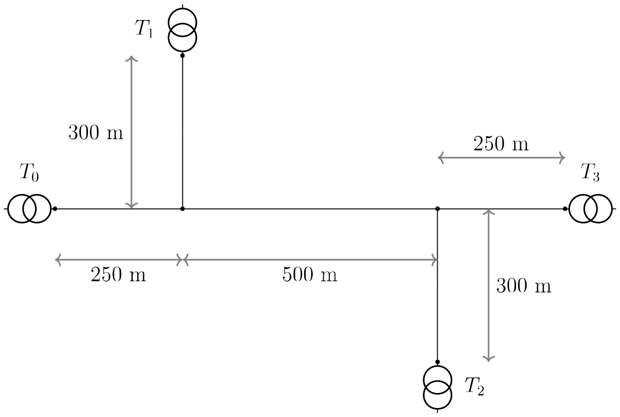

Figure 1 MV network (adapted from [9]). T_0 is the HV/MV transformer (132 kV/15 kV); the others are MV/LV transformers (15 kV/0.4 kV).

Table 1 Median (M) and logarithmic standard deviation (σ_{ln}) of log-normal distributions of lightning parameters from main literature references.

Parameter	M	σ_{ln}
Front duration neg. first strokes (µs)	5.5[a]	0.57[b]
Front duration neg. subsequent strokes (µs)	1.1[a]	0.92[b]
Front duration pos. strokes (µs)	22.0[a]	1.23[c]
Peak current neg. first strokes (kA)	31.1[d]	0.48[d]
Peak current neg. subsequent strokes (kA)	12.3[d]	0.53[d]
Peak current pos. strokes (kA)	35.0[c]	1.21[c]
Neg. flash multiplicity (-)	3.4[e]	0.96[e]
Neg. flash ground terminations distance (km)	1.7[f]	0.79[f]

[a] Provided in [13]
[b] Recomputed from T_{d10} [1]
[c] Provided in [10] on the basis of results from [13]
[d] Provided in [1] on the basis of results from [13]
[e] Provided in [1]
[f] Log-normal fitting of the histogram shown in [22]

two MV/LV transformers (T_1 and T_2). The high-frequency models of the transformers and the V-I characteristics of the surge arresters are consistent with those detailed in [9].

3.2 Lightning Distributions and Parameters

Lightning parameters are commonly assumed to follow log-normal distributions. Table 1 presents the median M and the logarithm standard deviation σ_{ln} provided by the main literature sources. Moreover, for the channel-base peak current of negative subsequent strokes, the negative flash multiplicity and the negative flash ground terminations distance, the employment of LLS data could be approriate [16, 17, 18, 22]. Therefore, for such parameters, M and σ_{ln} are extrapolated from the 10-year LLS data analysis in Italy shared in [18] and reported in Table 2.

In the following points an in-depth argumentation of various lightning parameters is provided.

1. Current front duration and peak current correlation: LLSs typically lack current front duration data. Thus, for simulations, distributions of such a parameter are taken from [13] (measurements at the instrumented tower of Monte San Salvatore). Moreover, the correlation between channel-base peak current and current front duration is considered in this work. The correlation coefficients are again assumed from [13] (i.e., 0.37, 0.28, and 0.07, for negative first, negative subsequent, and positive return strokes, respectively).

Table 2 Median (M) and logarithmic standard deviation (σ_{ln}) of log-normal distributions of lightning parameters from LLS data (Italy 2010-2019 [18]).

Parameter	M	σ_{ln}
Peak current neg. subsequent strokes (kA)	13.5	0.62
Neg. flash multiplicity (-)	0.8	1.02
Neg. flash ground terminations distance (km)	1.7	0.81

2. Channel-base peak current: the estimation of the current peak from the field peak performed by LLSs has been validated (through rocket-triggered lightning and direct tower measurements) only for negative subsequent strokes lower than 60 kA [16, 17]. Differences in the median peak current of positive and negative first strokes are evident between tower measurements and LLS estimations. Notably, the median peak current derived from LLSs for negative first strokes aligns with that of negative subsequent strokes, as reported in studies like [16, 18]. On the other hand, direct measurements report considerably higher median peak currents for the first stroke than subsequent strokes [13]. As a result, considering these discrepancies, for positive and negative first stroke peak currents the LP assessment focuses solely on conventional PDFs.

3. Negative flash multiplicity: the parameters of the log-normal distribution ($M = 3.4$, $\beta = 0.96$) of the number of stroke per flash are available in the standards (e.g., [1]); such distribution is used in this work as the reference one. However, the median multiplicity measured at the instrumented tower of Monte San Salvatore is 2.8, with a 39% occurrence of flashes with a single stroke [12]. Indirect records gathered across regions of various climes revealed median multiplicities ranging from 3 to 5 and percentages of single-stroke flashes between 14% and 21% [23]. However, the storm characteristics could influence such values, particularly with reduced sample sizes [24, 25]. Thus, the adoption of a huge amount of LLS data to estimate the negative flash multiplicity may mitigate this problem. LLS data typically yields markedly lower flash multiplicity values with respect to direct tower measurements [18, 26], likely due to potential failures in detecting subsequent return strokes with small peak current. Since the choice of the negative flash multiplicity PDF has been found to produce considerable effects on the expected number of flash-overs per year [11], a reliable estimation of such a parameter would contribute to improving the LP evaluation.

4. Distance between ground terminations of negative flashes: optical observations reported in [22] revealed that most subsequent stroke terminations are within 2

Table 3 Test cases for the assessment of the LP. The GFD is assumed to be unitary. In the second column, the acronyms 'nf', 'ns' and 'p' refer to negative first, negative subsequent and positive return strokes, respectively. Front duration PDFs and correlation coefficients with the peak current, as well as the PDF of the peak current for positive and negative first return strokes, are always assumed from the literature.

Case #	Return stroke types	Neg. subsequent strokes I PDF	Neg. flash multiplicity PDF	Neg. flash ground terminations dist. PDF	Flash polarity prob. (a_n, a_p)
A1	nf-ns	Conventional	Conventional	-	-
A2	nf-ns	Conventional	LLS-inferred	-	-
A3	nf-ns	LLS-inferred	Conventional	-	-
A4	nf-ns	LLS-inferred	LLS-inferred	-	-
B1	nf-ns	Conventional	Conventional	Conventional	-
B2	nf-ns	Conventional	LLS-inferred	Conventional	-
B3	nf-ns	LLS-inferred	Conventional	Conventional	-
B4	nf-ns	LLS-inferred	LLS-inferred	Conventional	-
B5	nf-ns	Conventional	Conventional	LLS-inferred	-
B6	nf-ns	Conventional	LLS-inferred	LLS-inferred	-
B7	nf-ns	LLS-inferred	Conventional	LLS-inferred	-
B8	nf-ns	LLS-inferred	LLS-inferred	LLS-inferred	-
C1	nf-ns-p	Conventional	Conventional	Conventional	Conventional
C2	nf-ns-p	Conventional	LLS-inferred	Conventional	Conventional
C3	nf-ns-p	LLS-inferred	Conventional	Conventional	Conventional
C4	nf-ns-p	LLS-inferred	LLS-inferred	Conventional	Conventional
C5	nf-ns-p	Conventional	Conventional	LLS-inferred	Conventional
C6	nf-ns-p	Conventional	LLS-inferred	LLS-inferred	Conventional
C7	nf-ns-p	LLS-inferred	Conventional	LLS-inferred	Conventional
C8	nf-ns-p	LLS-inferred	LLS-inferred	LLS-inferred	Conventional
C9	nf-ns-p	Conventional	Conventional	Conventional	LLS-inferred
C10	nf-ns-p	Conventional	LLS-inferred	Conventional	LLS-inferred
C11	nf-ns-p	LLS-inferred	Conventional	Conventional	LLS-inferred
C12	nf-ns-p	LLS-inferred	LLS-inferred	Conventional	LLS-inferred
C13	nf-ns-p	Conventional	Conventional	LLS-inferred	LLS-inferred
C14	nf-ns-p	Conventional	LLS-inferred	LLS-inferred	LLS-inferred
C15	nf-ns-p	LLS-inferred	Conventional	LLS-inferred	LLS-inferred
C16	nf-ns-p	LLS-inferred	LLS-inferred	LLS-inferred	LLS-inferred

km from the first stroke termination. The log-normal distribution parameters extrapolated from the measurements of [22] and the Italian LLS data [18] are almost the same.

5. Probability of flash polarity: a common assumption in application considers that 90% of total lightning are of negative polarity, leading to set $a_n = 0.90$ and $a_p = 0.10$ [10, 16]. However, the LLS data analysis reported in [18] revealed a larger occurrence of positive flashes (18%) .

6. Ground Flash Density (GFD) N_g: reliable estimation of N_g holds significance as it directly influences the count of annual flash-overs (F). $N_g = 1.78$ flashes km^{-2} yr^{-1} resulted from the 10-year LLS data analysis of [18], accounting for the whole extension of Italy. According to the IEEE Std. 1410 [1], methods based on satellite measurements, such as the Optical Transient Detector flash density (N_t) [27], may yield alternative estimates in the absence of local LLS data. Since N_t accounts for both ground and cloud discharges, it is suggested to approximate the GFD as $N_g = N_t/3$ [1]. Thus, for the sake of comparison, if the availability of LLS data is not considered, for Italy $N_t = 9.00$ flashes km^{-2} yr^{-1} [27]; hence, $N_g = 3.00$ flashes km^{-2} yr^{-1} may be an approximation of the GFD.

4 Results

According to the considerations on LLS data availability and accuracy discussed in the previous sections, different combinations of lightning parameters and distributions are considered with the aim of assessing the impact of the use of local data from LLSs on the LP evaluation (Table 3).

Cases A1, B1 and C1 are the benchmarks (only conventional parameters and PDFs). The effects produced by the progressive replacement of parameters and PDFs from conventional to LLS-inferred are studied.

Multi-stroke negative flashes are simulated in Cases A1-A4 by disregarding multiple ground terminations and assuming the first stroke striking point for all the strokes of the same flash. The distribution of ground terminations distance of negative flashes is introduced from Case B1. Finally, from Case C1 also the presence of positive strokes is considered.

The expected number of flash-overs per year F is computed as a function of the line CFO (which ranges between 50 kV and 250 kV) and shown in Figure 2. From panel (a), which depicts Cases A1-A4, it can be observed that when the negative flash multiplicity PDF is assumed from

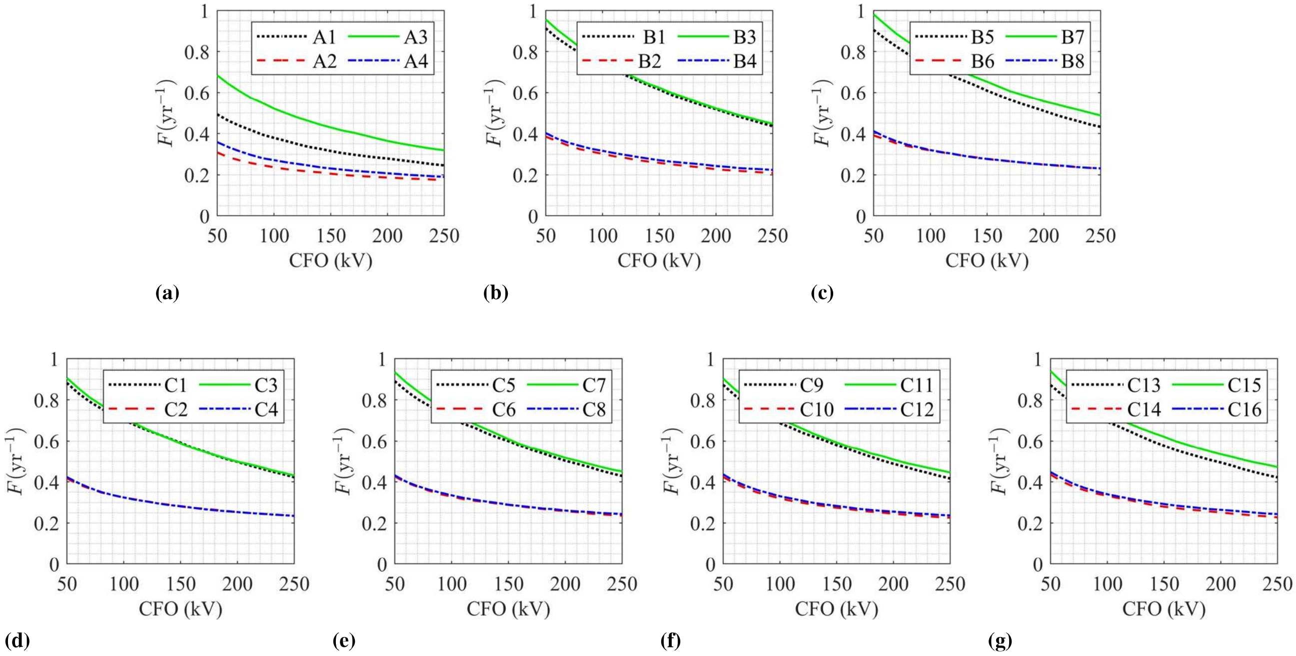

Figure 2 LP assessment results: expected number of flash-overs per year with $N_g = 1$ flash km^{-2} yr^{-1} against the line CFO. Case details in Table 3.

LLS data (Cases A2 and A4) instead of the standard one [1] (Cases A1 and A3), a lower F is estimated. On the other hand, the use of the LLS-inferred distribution of negative subsequent strokes results in an enhancement of F, appreciable with both the conventional multiplicity PDF (Case A3 vs Case A1) and the LLS-derived multiplicity PDF (Case A4 vs Case A2).

The log-normal distribution of the distance between ground terminations of negative flashes is considered in all the B Cases. Cases B1-B4 replicate Cases A1-A4 including the conventional PDF, whereas Cases B5-B8 replicate Cases A1-A4 including the LLS-inferred PDF, as shown in panels (b) and (c), respectively. Comparing the corresponding curves of panels (b) and (c), no significant variations are observed, since the two distributions are very close to each other. However, in accordance to what has been reported in [11], with a relevant flash multiplicity (i.e., the conventional log-normal [1]: $M = 3.4$, $\sigma_{ln} = 0.96$), higher values of F are observed when the ground terminations distance PDF is considered, as appears by comparing Cases B1 (B5) and B3 (B7) with Cases A1 and A3, respectively.

Curves of panels (d)-(g) are computed accounting for positive strokes, too. Cases C1-C8 replicate Cases B1-B8 including the conventional PDF whereas Cases C9-C16 replicate Cases B1-B8 including the LLS-inferred PDF. The occurrence of positive flashes resulting from the LLS data analysis [18] is 1.8 times the typical value [10, 16]. Nevertheless, with any negative flash multiplicity PDF, comparable results are obtained with the conventional flash polarity probability and with that extrapolated from LLS data. As discussed in [11], the effect produced by the inclusion of positive strokes in the LP is influenced by the selection of the distribution for the negative flash multiplicity. When the standard multiplicity PDF [1] is assumed, no substantial variations can be observed by comparing the corresponding curves with and without positive strokes, i.e., Cases C1 (C3), C5 (C7), C9 (C11) and C13 (C15) with Cases B1, B3, B5 and B7, respectively. On the other hand, when the LLS-inferred multiplicity PDF ($M = 0.8$, $\sigma_{ln} = 1.2$) [18] is assumed, the inclusion of positive strokes leads to a slight increase of F, as can be seen by comparing Cases C2 (C4), C6 (C8), C10 (C12) and C14 (C16) with Cases B2, B4, B6 and B8, respectively.

In conclusion, the estimated annual counts of flash-overs per year depicted in Figure 2 are expressed assuming $N_g = 1$ flash km^{-2} yr^{-1}. However, such values should be adjusted in accordance with the specific GFD. In the context of Italy, with the assumption of no availability of local LLS data, an estimation of the GFD as $N_g = 3.00$ flashes km^{-2} yr^{-1} can be obtained according to the IEEE Std. 1410 recommendations [1]. However, the LLS data analysis conducted in [18] yielded $N_g = 1.78$ flashes km^{-2} yr^{-1} (i.e., a 0.6 times lower value). This discrepancy implies a decrease of a factor 0.6 in the estimated F, when employing the same distribution scheme for lightning parameters.

5 Conclusion

This contribution has discussed the Lightning Performance (LP) evaluation of a distribution network in Italy including probability distributions of lightning parameters extrapolated from national Lightning Location System (LLS) data. Different types of return strokes and multiple ground terminations within a flash have been considered in the analysis. The effects on the annual counts of flash-overs (F) produced by the replacement (when possible and justified) of conventional distributions of lightning parameters with LLS-inferred distributions have been studied. Employing the negative subsequent stroke channel-base peak current distribution extrapolated from LLS data resulted in an appreciable higher value of F with respect to the benchmark distribution (provided by tower measurement campaigns). On the other hand, when the distribution of negative flash multiplicity is inferred from LLS data in place of that given by direct measurements, a reduction of the estimated F has been obtained. Considering the distribution of the distance of negative flash ground terminations produced a significant increase of F; however, the similarity between the LLS-inferred distribution and the conventional distribution led to comparable results. With the inclusion of positive strokes in the LP assessment, although the LLS recorded almost double the percentage of positive flashes compared to the conventional one, no noteworthy variations in the annual count of flash-overs have been observed. The findings of this paper underscore the potential utility of LLSs in enhancing the assessment of the LP of distribution networks. Consequently, additional efforts in improving and validating the use of LLS data to estimate lightning parameters would be desirable, with a particular focus on the negative first stroke channel-base peak current.

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7 Literature

[1] IEEE, "Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines," *IEEE Std. 1410-2010 (Revision of IEEE Std 1410-2004)*, pp. 1–73, 2011.

[2] A. Borghetti, C. A. Nucci, and M. Paolone, "Indirect-Lightning Performance of Overhead Distribution Networks With Complex Topology," *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp. 2206–2213, 2009.

[3] A. Borghetti, C. A. Nucci, and M. Paolone, "An Improved Procedure for the Assessment of Overhead Line Indirect Lightning Performance and Its Comparison with the IEEE Std. 1410 Method," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 684–692, 2007.

[4] M. Brignone, F. Delfino, R. Procopio, M. Rossi, and F. Rachidi, "Evaluation of Power System Lightning Performance - Part I: Model and Numerical Solution Using the PSCAD-EMTDC Platform," *IEEE Transactions on Electromagnetic Compatibility*, vol. 59, no. 1, 2017.

[5] D. Mestriner, M. Brignone, R. Procopio, M. Nicora, E. Fiori, A. Piantini, and F. Rachidi, "An Efficient Methodology for the Evaluation of the Lightning Performance of Overhead Lines," *IEEE Transactions on Electromagnetic Compatibility*, vol. 63, no. 4, pp. 1137–1145, 2021.

[6] M. Brignone, R. Procopio, M. Nicora, D. Mestriner, F. Rachidi, and M. Rubinstein, "A prony-based approach for accelerating the lightning electromagnetic fields computation above a perfectly conducting ground," *Electric Power Systems Research*, vol. 210, 2022. Cited by: 3.

[7] M. Brignone, R. Procopio, M. Nicora, D. Mestriner, F. Rachidi, and M. Rubinstein, "A prony-based approach for accelerating the lightning electromagnetic fields computation: Effect of the soil finite conductivity," *Electric Power Systems Research*, vol. 209, 2022.

[8] J. O. S. Paulino, C. F. Barbosa, I. J. S. Lopes, and W. C. Boaventura, "Assessment and analysis of indirect lightning performance of overhead lines," *Electric Power Systems Research*, vol. 118, pp. 55–61, 2015.

[9] M. Brignone, F. Delfino, R. Procopio, M. Rossi, and F. Rachidi, "Evaluation of Power System Lightning Performance - Part II: Application to an Overhead Distribution Network," *IEEE Transactions on Electromagnetic Compatibility*, vol. 59, no. 1, pp. 146–153, 2017.

[10] F. Napolitano, F. Tossani, A. Borghetti, C. A. Nucci, and F. Rachidi, "Lightning performance of distribution lines due to positive and negative indirect lightning flashes," in *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, pp. 1–5, 2017.

[11] M. Nicora, D. Mestriner, M. Brignone, R. Procopio, E. Fiori, A. Piantini, and F. Rachidi, "Estimation of the Lightning Performance of Overhead Lines Accounting for Different Types of Strokes and Multiple Strike Points," *IEEE Transactions on Electromagnetic Compatibility*, vol. 63, no. 6, pp. 2015–2023, 2021.

[12] K. Berger, "Novel observations on lightning discharges: Results of research on Mount San Salvatore," *Journal of the Franklin Institute*, vol. 283, no. 6, pp. 478–525, 1967.

[13] K. Berger, R. B. Anderson, and H. Kroninger, "Parameters of lightning flashes," *Electra*, vol. 41, pp. 23–37, 1975.

[14] S. Visacro, A. Soares Jr., M. A. O. Schroeder, L. C. L. Cherchiglia, and V. J. de Sousa, "Statistical analysis of lightning current parameters: Measurements at Morro do Cachimbo Station," *Journal of Geophysical Research: Atmospheres*, vol. 109, no. D1, 2004.

[15] C. Rovelli, M. Bernardi, and F. Rocchetti, "Estrapolation of the Median Value of the Lightning Current on the Basis of Existing Measurments," in *Proc. VIII International Symposium on Lightning Protection-SIPDA*, pp. 1544–1554, 2005.

[16] G. Diendorfer, M. Bernardi, K. Cummins, F. De La Rosa, B. Hermoso, A. Hussein, T. Kawamura, F. Rachidi, V. Rakov, W. Schulz, and H. Torres, "Cloud-to-Ground Lightning Parameters Derived from Lightning Location Systems – The Effects of System Performance (CIGRE TF C4.404)," 2009.

[17] F. Rachidi, J. L. Bermudez, M. Rubinstein, and V. A. Rakov, "On the estimation of lightning peak currents from measured fields using lightning location systems," *Journal of Electrostatics*, vol. 60, no. 2, pp. 121–129, 2004.

[18] M. Nicora, D. Mestriner, M. Brignone, M. Bernardi, R. Procopio, and E. Fiori, "A 10-year study on the lightning activity in Italy using data from the SIRF network," *Atmospheric Research*, vol. 256, p. 105552, 2021.

[19] M. Darveniza, "A Practical Extension of Rusck's Formula for Maximum Lightning-Induced Voltages That Accounts for Ground Resistivity," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 605–612, 2007.

[20] IEEE, "Estimating lightning performance of transmission lines. II - Updates to analytical models," *IEEE Transactions on Power Delivery*, vol. 8, no. 3, pp. 1254–1267, 1993.

[21] V. A. Rakov, "A Review of Positive and Bipolar Lightning Discharges," *Bull. Amer. Meteor. Soc.*, vol. 84, no. 6, pp. 767–776, 2003.

[22] R. Thottappillil, V. A. Rakov, M. A. Uman, W. H. Beasley, M. J. Master, and D. V. Shelukhin, "Lightning subsequent-stroke electric field peak greater than the first stroke peak and multiple ground terminations," *J. Geophys. Res.*, vol. 97, no. D7, pp. 7503–7509, 1992.

[23] M. G. Ballarotti, C. Medeiros, M. M. F. Saba, W. Schulz, and O. Pinto Jr., "Frequency distributions of some parameters of negative downward lightning flashes based on accurate-stroke-count studies," *J. Geophys. Res.*, vol. 117, no. D6, 2012.

[24] Y. Zhu, V. A. Rakov, S. Mallick, and M. D. Tran, "Characterization of negative cloud-to-ground lightning in Florida," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 136, pp. 8–15, 2015.

[25] C. J. Biagi, K. L. Cummins, K. E. Kehoe, and E. P. Krider, "National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004," *Journal of Geophysical Research: Atmospheres*, vol. 112, no. D5, 2007.

[26] D. R. Poelman, W. Schulz, G. Diendorfer, and M. Bernardi, "The European lightning location system EUCLID – Part 2: Observa-

tions," *Nat. Hazards Earth Syst. Sci.*, vol. 16, no. 2, pp. 607–616, 2016.

[27] H. J. Christian, R. J. Blakeslee, D. J. Boccippio, W. L. Boeck, D. E. Buechler, K. T. Driscoll, S. J. Goodman, J. M. Hall, W. J. Koshak, D. M. Mach, and M. F. Stewart, "Global frequency and distribution of lightning as observed from space by the Optical Transient Detector," *Journal of Geophysical Research: Atmospheres*, vol. 108, no. D1, pp. ACL 4–1–ACL 4–15, 2003.