



21, rue d'Artois, F-75008 PARIS  
[http : //www.cigre.org](http://www.cigre.org)

0505

ZAGREB 2007

## A METHOD FOR THE ASSESSMENT OF THE INDIRECT LIGHTNING PERFORMANCE OF DISTRIBUTION NETWORKS

A. Borghetti, C.A. Nucci, M. Paolone  
University of Bologna, Italy

### SUMMARY

The paper presents a general procedure for the evaluation of the indirect lightning performance of a distribution network, which takes into account the actual network topology and the presence of transformers, surge arresters and line poles. The procedure is an extension of a Monte Carlo-based approach developed for a single straight overhead line to the case of a more complex distribution network consisting of a number of lines (main feeder and laterals) and typical power components. The procedure is based on the accurate evaluation of the induced voltages along the network, achieved by using the LIOV-EMTP computer code, which combines a model for the calculation of lightning-induced overvoltages (LIOV) on overhead lines with the electromagnetic transient program (EMTP). In order to reduce the required computational effort, a heuristic technique is proposed and its accuracy is verified. Finally, the paper presents a comparison between the lightning performances of distribution networks characterized by the same overall length of overhead lines but with different topologies. The effects of the presence of line poles, transformers and surge arresters are also analysed.

### KEYWORDS

Lightning-induced overvoltages, lightning performance, power quality, distribution networks, overhead power lines, LIOV-EMTP.

### 1. INTRODUCTION

One of the main aspects of insulation coordination of overhead power distribution networks is the evaluation of the annual number of flashovers caused by indirect lightning [1]. This is generally denoted with the term 'indirect lightning performance' of the network of interest. Such an evaluation has a significant impact on the choice of the insulation levels of the network components as well as on the design of the protection system, essentially composed by grounded shield wires and/or surge arresters [2].

The evaluation of the lightning performance of overhead distribution line has been the object of several studies; the IEEE Std. Guide 1410 [3] recommends, for instance, a procedure based on a simplified evaluation of the lightning induced overvoltages. A Monte Carlo procedure has been proposed the authors in [4] and has been there compared with the above-mentioned

one by IEEE. The use of such a procedure allows for a more accurate evaluation of the lightning performance of finite-length multi-conductor straight lines above a lossy ground.

This paper presents an extension of this Monte Carlo-based procedure to the case of topologically-complex distribution networks consisting of several lines (e.g. a main feeder plus laterals). The improved procedure is based, as the previous one, on the use of the LIOV code for the time-domain simulation of the LEMP-induced voltages along the overhead lines [5]. By taking advantage of the interface between the LIOV code and the electromagnetic transient program (EMTP) – which has made it possible to realize a software tool called LIOV-EMTP [6,7] – the procedure can analyse distribution systems with any configuration.

In order to reduce and optimize the high computational effort required by the Monte Carlo method, a heuristic technique has been developed for the reduction of the number of events that needs to be computed by using the LIOV-EMTP code.

The paper is structured as follows. Section 2 contains a brief description of the Monte Carlo based procedure and its application to the case of a distribution network. Section 3 presents the above-mentioned heuristic technique and the validation of its accuracy. Sections 4 and 5 present an analysis aimed at showing the influence of the network topology and of the presence of various power components, on the indirect lightning performance.

## 2. PROCEDURE FOR THE EVALUATION OF THE INDIRECT LIGHTNING PERFORMANCE

The procedure is defined by the following steps:

- a) A large number of lightning events  $n_{tot}$  is randomly generated. Each event is characterized by four parameters: lightning current amplitude  $I$ , time to peak  $t_f$ <sup>1</sup> and stroke location  $P$  with coordinates  $x$  and  $y$ . The first two values, namely  $I$  and  $t_f$ , characterize the lightning current waveform at the channel base and are assumed to follow the Cigré log-normal probability distributions [8,9] for negative first strokes<sup>2</sup>, with a correlation coefficient, between  $t_f$  and  $I$ , equal to 0.47 [8]. The stroke locations are assumed to be uniformly distributed in a so-called indirect striking area around the network, with size  $A$  (in km<sup>2</sup>), beyond which it is assumed that none of the lightning events could cause a flash on the lines.
- b) From the total set of events, those relevant to indirect lightning are selected by adopting a lightning incidence model for the line. The results of this paper have been obtained by using the same electrogeometric lightning incidence model (EGM) adopted by IEEE Std. 1410.
- c) For each of the indirect lightning events  $n_{tot,ind}$ , the maximum induced voltage value on the various lines of the distribution network are calculated – as already mentioned – by means of the LIOV-EMTP code.
- d) Defining  $n$  the number of events generating induced voltages larger than the considered insulation level, the annual number of events that induce voltages greater than the insulation level is obtained from the following expression:

$$F_p = \frac{n}{n_{tot,ind}} \cdot N_g \cdot A \quad (1)$$

where  $N_g$  is the annual lightning ground flash density (in km<sup>-2</sup> yr<sup>-1</sup>). Note that in order to infer the annual number of flashovers due to indirect lightning one should take into account the voltage-time characteristic of the insulator chain, an issue that we deliberately disregard

---

<sup>1</sup> The lightning return-stroke current waveform is assumed to have the shape of linear ramp until the peak value  $I$  is reached at time  $t_f$ , then followed by a constant value ( $I$ ). Although more accurate lightning waveforms have been proposed, it is here assumed that they produce induced-voltage amplitudes close to those estimated by using the earlier mentioned ramp to flat-top waveform, provided they exhibit the same amplitudes and same average steepness between the 30% and 90% amplitude intercepts.

<sup>2</sup> As done by the IEEE Std. method, only first return strokes are taken into account in our analysis.

in this paper. For this reason the lightning performance of the distribution networks that will be presented in the following sections are expressed in terms of annual number of events exceeding the voltage value reported in abscissa..

### 3. HEURISTIC TECHNIQUE FOR THE OPTIMIZATION OF THE CALCULATION PROCESS

In order to perform the statistical analysis over an adequate number of random generated events while maintaining a reasonably low computational time, we have implemented a heuristic procedure that, for the LIOV-EMTP calculations, selects only those events with some probability to induce dangerous voltages, i.e. with amplitudes larger than the considered minimum line-insulation level  $\bar{V}$ .

The heuristic technique, as it will be described later in details, progressively discards events by comparing their characteristics with those of the previously calculated ones. Therefore, the larger the number of the already considered events, the lower the probability that the following events require LIOV-EMTP calculations.

#### 3.1. Description of the heuristic technique

Let assume that for  $i-1$  events the maximum induced overvoltages have been already calculated. Each event  $k$ ,  $k \in \{1, \dots, i-1\}$ , is characterized by the four input quantities – namely  $I_k$ ,  $t_{f,k}$ , and  $P_k$  with coordinates  $x_k$  and  $y_k$  – and the maximum value  $V_{\max,k}$  of the induced voltage amplitudes calculated at each line pole. As shown in Fig. 1, for any stroke whose maximum induced voltage is lower than  $\bar{V}$ , the technique considers a circular area  $\Omega_k$  centred in  $P_k$ , whose radius  $r_k$  has been properly selected in the range between 50 m and 100 m. Moreover, other two circular areas  $\Omega_{k,j1}$ , and  $\Omega_{k,j2}$  are defined, each centred in the two poles ( $j1$  and  $j2$ ) closest to stroke location  $P_k$ , with radii  $r_{k,j1}$  and  $r_{k,j2}$  respectively equal to the distance between the relevant pole and the stroke location. Area  $\Omega_k^*$  is then defined as the sub-area of  $\Omega_k$  corresponding to the relative complement of the union of  $\Omega_{k,j1}$  and  $\Omega_{k,j2}$  in  $\Omega_k$ , namely  $\Omega_k^* = \Omega_k - \{\Omega_{k,j1} \cup \Omega_{k,j2}\}$ . As shown in Fig. 1, sub-area  $\Omega_k^*$  defines the points of  $\Omega_k$  whose distance from the nearest poles are larger than that of stroke location  $P_k$ .

Now, the induced voltages relevant to the  $i$ -th event are not analysed by using the LIOV-EMTP code and not included in the number  $n$  of events that could cause a flashover, if the following conditions are satisfied:

- 1)  $V_{\max,k} < \bar{V}$
- 2)  $P_i \in \Omega_k^*$
- 3)  $I_i \leq I_k$
- 4)  $t_{fi} \geq t_k$

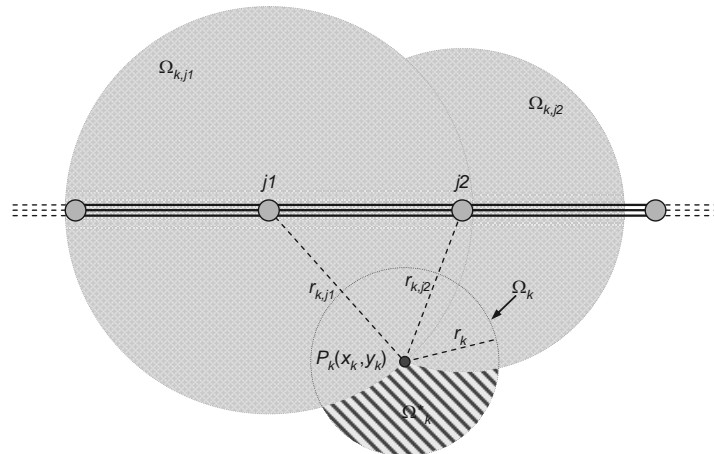


Fig. 1. Scheme of the heuristic procedure

### 3.2. Numerical validation of the heuristic procedure

In order to numerically validate the heuristic procedure, we consider the case of a *H*-shaped distribution network of 2 km total length and five overhead lines with a 1.2 km-long main feeder and four 0.2 km-long laterals (see Fig. 2). The overhead lines are 10 m high, single-conductor lines above an ideal ground with span length between poles of 100 m. The calculation of the lightning-induced overvoltages is performed in correspondence of the line poles. In view of the symmetrical property of the network topology, the considered striking area is a quarter of the total area around the network; it is equal to 1.92 km<sup>2</sup>, corresponding to a distance larger than 1 km all around the network. The number of considered Monte Carlo events in the striking area is 10 000.

Without the application of the heuristic technique, all the events corresponding to an indirect lightning (namely,  $n_{\text{tot,ind}} = 9681$  for the considered network topology) should be analysed by LIOV-EMTP simulations. By applying the heuristic technique, the number of events that need to be analysed decreases as the value  $r_k$  increases, as shown in Table I.

Table I. Comparison of the percentage of events that require to be analysed by means of LIOV-EMTP simulations for various values of parameter  $r_k$  of the heuristic technique.

$r_k$ value	percentage of indirect lightning events analysed by LIOV-EMTP simulations
without heuristic	100 %
$r_k=100$ m	30 %
$r_k=400$ m	10 %
$r_k=600$ m	8 %

Table II shows the comparison between the indirect lightning performance  $F_p$  calculated by applying the heuristic technique for the different values of  $r_k$  shown in Table I and by applying the proposed procedure without the heuristic technique. The results show that only for very low insulation levels, namely 50 and 75 kV, some differences are obtained.

Table II. Indirect lightning performance values  $F_p$  of the H-shaped distribution network of Fig. 2 calculated by using the proposed procedure without the heuristic technique and by applying the heuristic technique for the different values of  $r_k$  of Table I.

Insulation level (kV)	$F_p$ calculated without heuristic	$F_p$ calculated by using the heuristic technique		
		$r_k= 100$ m	$r_k= 400$ m	$r_k= 600$ m
50	0.379	0.379	0.322	0.283
75	0.150	0.150	0.149	0.141
100	0.065	0.065	0.065	0.065
125	0.028	0.028	0.028	0.028
150	0.015	0.015	0.015	0.015
175	0.005	0.005	0.005	0.005
200	0.003	0.003	0.003	0.003

Fig. 2 shows the top view of the distribution network. It also shows the stroke locations of the random events for which the LIOV-EMTP calculation has been performed and those of the events directly disregarded by the heuristic technique (with  $r_k=100$  m).

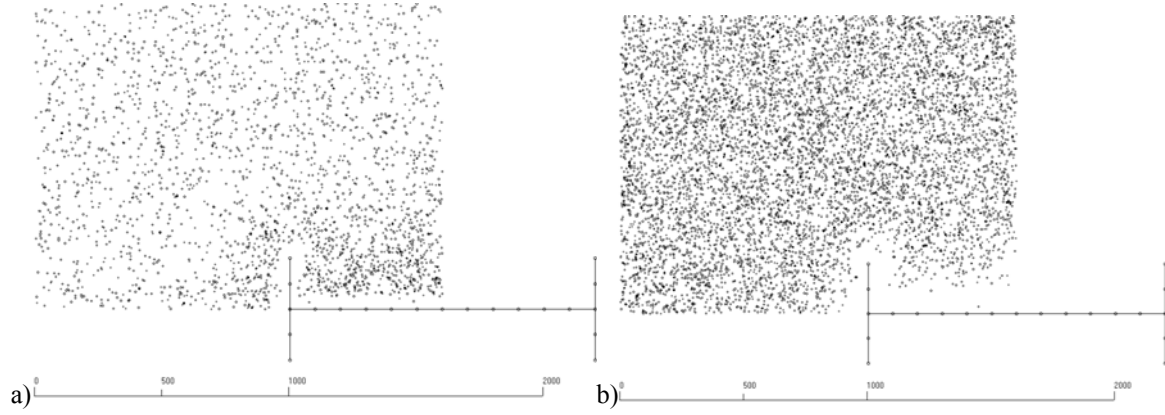


Fig. 2. Top view of the distribution network topology and stroke locations with  $r_k=100$  m: a) calculated events; b) non-calculated events directly identified by the heuristic technique.

As it can be seen from Table I and Table II, the use of the heuristic procedure allows obtaining the same results of the benchmark case for  $r_k$  lower than 100 m and a reduction of the total computational time of about 70 %. Note that larger values of  $r_k$  (e.g. 400 m) allows to obtain the same results of the benchmark case for  $\bar{V} > 100$  kV with an additional decrease of the computational load.

#### 4. INFLUENCE OF THE NETWORK TOPOLOGY ON ITS INDIRECT LIGHTNING PERFORMANCE

Most of the works on lightning-induced voltages make reference to single or multi-conductor straight lines. Distribution systems are, however, of different and more complex topologies, as they generally consist of one or more main feeders and several laterals. In [10] the adequacy of replacing one or more branches of complex networks with transmission lines assumed as non-illuminated by the lightning electromagnetic pulse has been investigated. This section of the paper is aimed at analysing the influence of the network topology on its indirect lightning performance. To analyse such an influence, the four configurations reported in Table III are considered. They make reference to two *H*-shaped networks, a *T*-shaped one and a straight line. In order to compare the lightning performance of these different topologies, they are assumed with the same length, equal to 2 km, and composed by single conductor overhead lines with poles placed each 100 m. Additionally, in order to analyze only the influence of the network topology, the presence of complex line termination, as well as of protection devices (e.g surge arresters and shield wire groundings), is disregarded. All the calculations have been carried out by using above described heuristic procedure assuming  $r_k = 100$  m.

Table III. Considered network topologies.

Network configuration	Relevant Shape
<i>H</i> -shaped type 1	
<i>H</i> -shaped type 2	
<i>T</i> -shaped	
Straight line	

Fig. 3 shows the lightning performance curves relevant to the topologies reported in Table III. As it can be seen the worst lightning performance is obtained for the “straight line” topology and an improvement of such a performance can be observed in correspondence of topologies that becomes more compact (e.g “*H*-shaped type 2”). In order to explain such a result, let us consider the network topology “*H*-shaped type 2” and compare it with the “*T*-shaped” one. The first topology is characterized by shorter branches that, in view of the effects relevant to the line length on the lightning induced voltages described in [5], result in a decrease of the lightning induced voltages compared to the longer branches of the “*T*-shaped” topology. To support this results, Fig. 4 shows the stroke locations of the random events selected by the heuristic procedure for the calculation with the LIOV-EMTP. As above described, these events are selected since they are expected to produce induced voltages  $\bar{V} > 50$  kV. Considering that the stroke locations which produce the largest influence on the lightning performance are those close to the network lines, it can be seen from Fig. 4 that the density of such stroke locations for the “*H*-shaped type 2” network (Fig. 4a) is lower than the same density of the “*T*-shaped” network (Fig. 4b) and of the “straight line” network (Fig. 4c). A general conclusion that can be inferred from the obtained results is that the network topology does have an influence on the lightning performance curve and that does produce a significant variation from the ‘standard results’ obtained when assuming a straight-line configuration. It is worth adding, however, that this result is influenced by the type of network topologies that we have examined. This means that, in general, when assessing the lightning performance of a distribution system, it is more appropriate referring to the specific topology of the distribution system of interest; on the other hand, the typical topology of certain rural distribution systems [11] – characterised by long line feeders – may make it still reasonable for these lines, the adoption of a single straight-line topology approach.

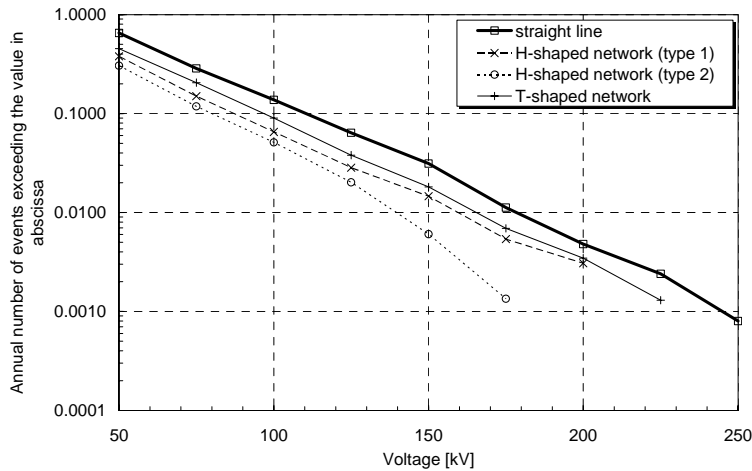


Fig. 3. Influence of the network topology on its lightning performance (topologies reported in Table III).

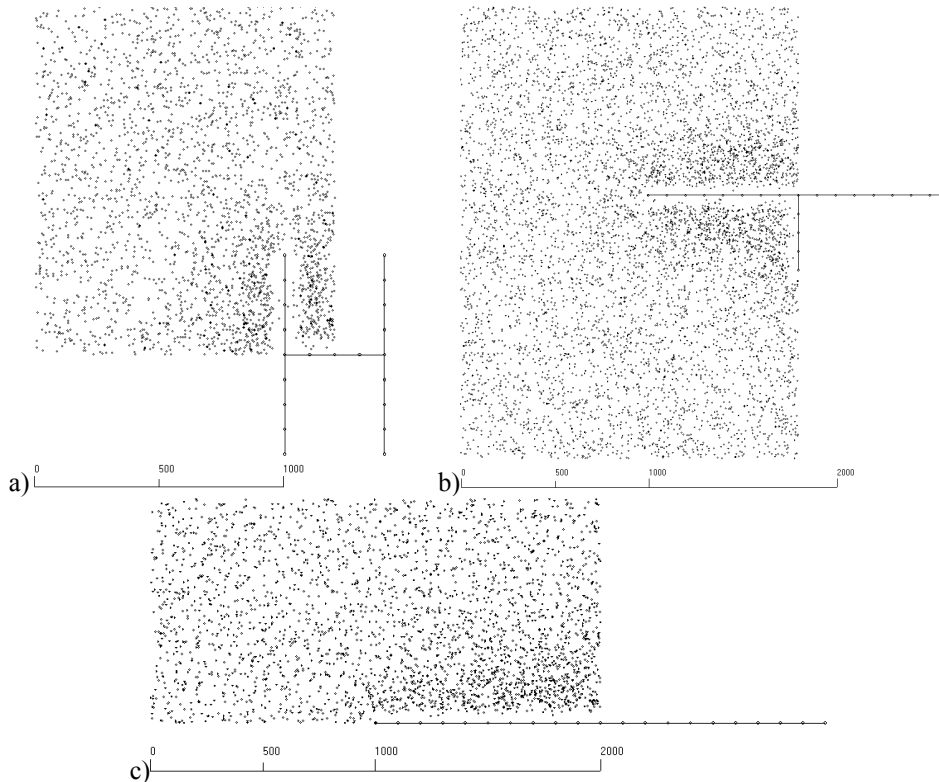


Fig. 4. Top view of the different network topologies and stroke locations selected by the heuristic procedure ( $r_k=100$  m): a) “*H*-shaped type 2” network; b) “*T*-shaped” network and c) straight line.

## 5. PRESENCE OF POWER TRANSFORMERS, SURGE ARRESTERS AND LINE POLES: THEIR INFLUENCE ON THE NETWORK PERFORMANCE

### 5.1 Power transformers and surge arresters

As mentioned in previous sections, more specific lightning performance curves can be obtained by considering the real network topology as well as the presence of additional power components. This section of the paper illustrates the results obtained making reference to the network topology “*H*-shaped type 1” of Table III, in which the network branch terminations are connected to power transformers protected by surge arresters<sup>3</sup>. In order to simulate, in a first approximation, the power transformer response for transients in a frequency range around 100 kHz, a  $\Pi$  of capacitances is considered as described in [13]. The value of the power transformer capacitance is of 250 pF.

Fig. 5 shows the lightning performance curves obtained for the “*H*-shaped type 1” network for the cases of matched line terminations and for terminations with power transformers protected by surge arresters. According to the findings of [5,14,15], the lightning performance of the system may be even worsened by the presence of surge arresters. This is due to the surge reflections occurring in correspondence of surge arrester operations, particularly important for the considered large spacing between consecutive arrester stations placed on in correspondence of line terminations.

<sup>3</sup> According to the indications reported in [14], the surge arresters are modeled using  $V-I$  nonlinear characteristics, which have been obtained by the standard 1.2/50  $\mu$ s pulse test on a typical 20 kV surge arrester [12].

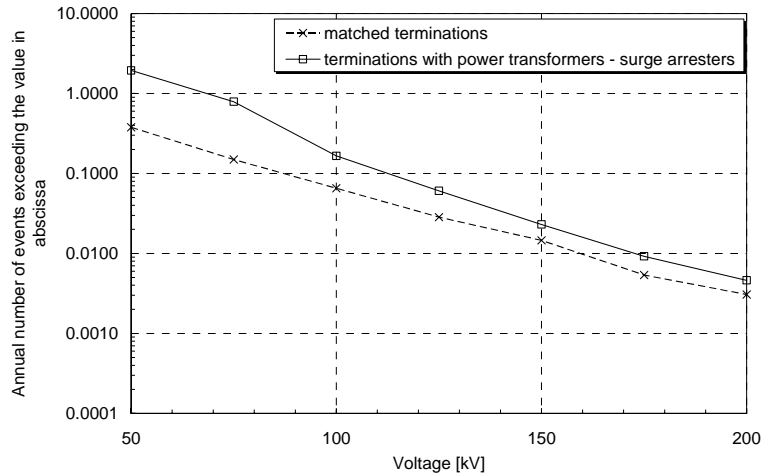


Fig. 5. Lightning performance curves obtained for the “H-shaped type 1” network for the cases of matched line terminations and terminations with power transformers protected by surge arresters.

### 5.2 Line poles

As already mentioned, in all the previous section we have calculated the induced voltages at the pole locations. In many papers of the literature on the subject, the lightning performance is calculated assuming that maximum values of lightning-induced voltages can occur in a generic point along the line, disregarding the fact that the flashovers occur in correspondence of line poles.

Fig. 6 shows the comparison of the results calculated by assuming that the maximum values can occur at any point along the lines with those obtained when the voltage observation points are situated only in correspondence of the line poles (100 m span). The line is 2-km long, single-conductor, situated above an ideal ground. It can be noted that when the observation points are situated in correspondence of the line poles, we obtain an overall reduction of the predicted annual number of flashovers, which we consider to be a more appropriate result.

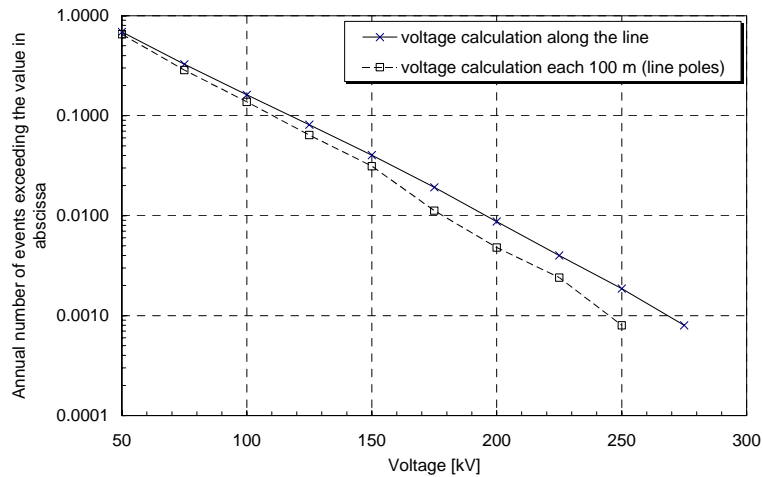


Fig. 6. Influence of the voltage calculation points on the lightning performance of a straight 2 km long single conductor line.

## VI. CONCLUSIONS

This paper has presented a procedure for the evaluation of the indirect lightning performances of distribution networks. The procedure takes into account the real network topology and the presence of power components, such as power transformers, surge arresters connected to the network, as well as the presence of line poles. The proposed method is based on the use of a)



the LIOV-EMTP code for the calculation of the lightning-induced voltages and b) the Monte Carlo method for the statistical evaluation of the frequency of the lightning-induced voltages exceeding the line insulation level. In order to reduce the computational load required by the proposed methodology, a heuristic procedure has been presented and numerically validated. The effectiveness of such a procedure has been analyzed and discussed in terms of accuracy and benefits; its adoption results in a significant reduction of the total computational load, up to 70%.

The application of the proposed procedure to a set of distribution networks characterized by the same overall length of the relevant overhead lines, but by different topologies, allows to conclude that, in general, when it is desired to assess the so-called lightning performance of a distribution network, one should make reference to the real topology of the system. A single straight-line approach may result into a misestimation of the indirect lightning performance of distribution networks.

## REFERENCES

- [1] Joint Cigré-Cired WG C4.4.02, "Protection of MV and LV networks against lightning. Part I: common topics", Cigré technical brochure, Nr. 287, February 2006.
- [2] A. R. Hileman, "Insulation coordination for power systems", Marcel Dekker Inc., New York– Basel, 1999.
- [3] IEEE Working Group on the lightning performance of distribution lines, "Guide for improving the lightning performance of electric power overhead distribution lines", IEEE Std 1410, 2004.
- [4] A. Borghetti, C.A. Nucci, M. Paolone, "An Improved Procedure for the Assessment of Overhead Line Indirect Lightning Performance and its Comparison with the IEEE Std. 1410 Method", IEEE Trans. on Power Delivery, vol. 22, no. 1, pp. 684-692, January 2007.
- [5] C.A. Nucci, F. Rachidi, "Interaction of electromagnetic fields with electrical networks generated by lightning", Chapter 8 of 'The Lightning Flash: Physical and Engineering Aspects', IEE Power and Energy series 34, IEE Press, 2003.
- [6] C.A. Nucci, V. Bardazzi, R. Iorio, A. Mansoldo, A. Porrino, "A code for the calculation of lightning-induced overvoltages and its interface with the electromagnetic transient program", Proc. Of the 22nd International Conference on Lightning Protection (ICLP), Budapest, Hungary, 1994.
- [7] A. Borghetti, J.A. Gutierrez, C.A. Nucci, M. Paolone, E. Petrache, F. Rachidi, "Lightning-induced voltages on complex distribution systems: models, advanced software tools and experimental validation", Journal of Electrostatics, Vol. 60/2-4, pp. 163-174, Elsevier, 2004.
- [8] R. B. Anderson and A. J. Eriksson, "Lightning parameters for engineering application," Electra, vol. 69, pp. 65–102, 1980.
- [9] Cigré Working Group 01 of SC 33, Guide to Procedures for Estimating the Lightning Performance of Transmission Lines Cigré, ref. no. 63, Oct. 1991.
- [10] E. Perez, M. Paolone, A Borghetti, C.A. Nucci, H. Torres, F. Rachidi, "On the Comparison Between Experimental Results and Calculations of Lightning-Induced Voltages on Distribution Systems – Effect Of The Distribution Network Topology", Proc. of the VIII International Symposium on Lightning Protection, Sao Paulo, Brasil, 21-25 November 2005, pp. 3-17.
- [11] IEEE Distribution Planning Working Group, "Radial Distribution Test Feeders", IEEE Trans. on Power Systems Vol. 6, No. 3, August 1991, pp 975-985.
- [12] IEEE Fast Front Transients Task Force, "Modeling guidelines for fast front transients," IEEE Trans. Power Del., vol. 11, no. 1, pp. 493–506, Jan. 1996.
- [13] A. Borghetti, A. S. Morched, F. Napolitano, C.A. Nucci, M. Paolone, "Lightning-Induced Overvoltages Transferred from Medium-Voltage to Low-Voltage Networks", Proc. Of the IEEE St. Petersburg Power Tech, 27-30 June 2005, St. Petersburg, Russia.
- [14] M. Paolone, C. A. Nucci, E. Petrache, and F. Rachidi, "Mitigation of lightning-induced overvoltages in medium voltage distribution lines by means of periodical grounding of shielding wires and of surge arresters: modeling and experimental validation," IEEE Trans. Power Del., vol. 19, no. 1, pp. 423–431, Jan. 2004.

[15] A. Borghetti, C. A. Nucci, M. Paolone, M. Bernardi, S. Malgarotti, and I. Mastandrea, "Influence of surge arresters on the statistical evaluation of lightning performance of distribution lines," presented at the Int. Conf. Probabilistic Methods Applied to Power Systems, Sep. 12–16, 2004.