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Statistical Evaluation of Lightning Performances of Distribution Lines

A. Borghetti C.A. Nucci M. Paolone
University of Bologna
Department of Electrical Engineering
40136 Bologna, Italy
{alberto.borghetti, carloalberto.nucci, mario.paolone}@mail.ing.unibo.it

Abstract - **Flashover rates of overhead multiconductor distribution lines with realistic configurations, due to lightning-induced overvoltages are estimated by means of a statistical procedure based on the Monte Carlo method. The goal is the estimation of the number of events exceeding, for a given ground flash density, a certain voltage value or – provided the voltage-time characteristic of the insulators is known – the 'classical' flashover rate *vs* CFO (critical flashover voltage) curves. For each lightning event, the evaluation of the induced overvoltage along the line is performed using the LIOV program, developed in the framework of an Italian-Swiss research collaboration. The procedure is first compared with the one proposed in the IEEE Guide Std 1410 for the same purpose, and then applied to a typical Italian line configuration.**

Keywords: Lightning induced voltages, Insulation coordination, MV lines, Lightning performance of distribution lines.

I. INTRODUCTION

As known, in medium voltage (MV) and low voltage (LV) distribution networks, dangerous overvoltages can be induced by lightning strokes hitting the ground in the vicinity of a line (lightning induced overvoltages). Due to the limited height of distribution lines compared to that of the structures in their vicinity, indirect lightning return strokes are in general more frequent events than direct strokes [1,2]: for this reason we shall deal only with induced voltages.

The paper presents lightning-induced flashover rates of overhead multi-conductor distribution lines. The calculations are carried out following the procedure based on the Monte Carlo method presented in [3], in which some additional improvements, which will be illustrated in Section 2, have been recently introduced. The output of the relevant program is the number of events that, for a given flash density and line length, induce an overvoltage with amplitude exceeding a given value. This, in turn, allows estimating the frequency distribution of lightning-induced voltages for a specific line and, provided the voltage-time characteristic of the insulator is known [4], it allows also the estimation of the "classical" flashover rate VS critical flashover voltage (CFO) curves.

After a brief description of the models and the method at the basis of the procedure presented in [3], in Section 2 we shall illustrate the earlier mentioned additional features, which allow for the taking into account of the steady-state voltage and of the change of coupling factor among the line conductors and the ground at the location where flashovers occur. In Section 3, we shall compare our method with the one proposed by the IEEE Guide Std 1410 [2] for the same purpose. Then in Section 4, we shall perform a first assessment of the lightning performance of a typical Italian distribution line. Section 5 is devoted to the conclusions.

II. MONTE-CARLO-BASED PROCEDURE TO EVALUATE THE INDIRECT-LIGHTNING PERFORMANCE OF DISTRIBUTION LINES

The evaluation of the lightning performance of a distribution line requires the accurate modeling of the induction mechanism. Several other phenomena (e.g. corona) as well as the presence of power components along the line must be properly modeled too. The large number of factors play an important role makes the problem still a challenge and, as a result, some complex procedures have been recently proposed which cover several aspects of the problem (e.g. [3,4]).

In what follows we shall briefly describe the procedure recently proposed in [3], which is based on an accurate modeling of the lightning induced voltage mechanism and on the Monte Carlo technique, with its recently introduced additional features.

2.1 Evaluation of the induced voltages

In the proposed method, the lightning-induced voltages are calculated using the LIOV (Lightning induced overvoltage) computer code. The LIOV code has been developed in the framework of an international collaboration involving the University of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome "La Sapienza" (Department of Electrical Engineering). The code is based on the field-to-transmission line coupling formulation of *Agrawal et al.* [5], suitably adapted for the case of an overhead line illuminated by an indirect lightning electromagnetic field [6,7].

According to the Agrawal coupling model, the forcing functions that excite the line are the horizontal and vertical components of the so called *incident* electric field, namely the sum of the field radiated by the lightning return stroke and the ground-reflected field in absence of the line wires. The total field is the sum of the incident field and the field *scattered* by the line. The total voltage $u_k(x,t)$, induced at point x of the generic k^{th} conductor of a multi-conductor line at time t, is given by [5-7]

$$u_k(x,t)=u_k^i(x,t)+u_k^s(x,t) \tag{1}$$

where $u_k^s(x,t)$ is the scattered voltage and $u_k^i(x,t)$ is the so-called incident voltage, defined by

$$u_k^i(x,t)=-\int_0^{h_k} \tag{2}$$

in which $E_{z_k}^i(x,z,t)$ is the vertical component of the incident electric field and h_k is the height of the k^{th} conductor of the multi-conductor line.

The vector of the scattered voltages $[u^s(x,t)]$ can be obtained from the solution of the following coupling equations

$$\frac{\partial}{\partial x}\left[u^s(x,t)\right]+\left[L'\right]\frac{\partial}{\partial t}\left[i(x,t)\right]+\left[\xi'_g\right]\otimes\frac{\partial}{\partial t}\left[i(x,t)\right]= \\ =\left[E_x^i(x,h_k,t)\right] \tag{3}$$

$$\frac{\partial}{\partial x}\left[i(x,t)\right]+\left[C'\right]\frac{\partial}{\partial t}\left[u^s(x,t)\right]=0 \tag{4}$$

in which

- $[L']$, and $[C']$ are the matrices of line per-unit-length inductance and capacitance respectively;
- $[\xi'_g]$ is the matrix of the transient ground impedance (the wire impedance is here neglected [7]);
- $[E_x^e(x,h_k,t)]$ is the vector of the horizontal components of the exciting (*incident*) electric field at point x of the various line conductors;
- $[i(x,t)]$ is the vector of the currents at point x of the various line conductors;
- $\otimes$ denotes the convolution product.

In the LIOV code, the incident vertical electric field is calculated using the electromagnetic field equations in the form given by *Uman* et al. [8] and the horizontal electric field is calculated using the *Cooray* and *Rubinstein* formula [9,10]. For the description of the spatial-temporal distribution of the lightning current along the return-stroke channel, it is adoped the Modified Transmission Line (MTL) return-stroke current model [11,12].

The LIOV code allows for the calculation of lightning-induced voltages along a multi-conductor overhead line as a function of several parameters: lightning return-stroke channel-base current waveshape, return-stroke velocity, line geometry (height, length, number and position of conductors), stroke location with respect to the line, ground resisitivity, relative permittivity, and termination impedances. Although, as mentioned, the induced voltage can be calculated starting from any waveform of the lightning current at the channel base, in order to reduce the computation time, the current waveshape is approximated with a ramp until the peak value I_p is reached at time t_f, then the current amplitude is kept constant. Lightning currents with different waveshape, but with the same amplitude and average steepness between the 30 and 90 percent amplitude intercepts, are reasonably assumed to give similar induced voltages.

2.2 Application of the Monte Carlo method

The lightning performance evaluation of distribution lines is based on the application of the Monte Carlo technique. We consider an energized line and generate an adequate number of events (at least 10 000). Each event is characterized by the following random variables: the value of the steady state voltage for each of the three phases (as it will be described in Sect. 2.3), the peak value of the lightning current I_p, its time to peak t_f and the position of the stroke location with respect to the line. Note that, when the ground conductivity is different from zero, the maximum induced voltage does not necessarily occur at the point closest to the stroke location, which makes it suitable for the analysis to consider a matched line of finite length within an indirect stroke location area [3]. The area must be wide enough to include all the lightning events that can induce a voltage that causes an insulation flashover. Typically, we consider a 1-2 km long line centered within an indirect stroke area of 4-8 km^2.

The values of current amplitude I_p and time-to-peak t_f are randomly generated from the relevant lognormal distribution published in [13]. The value t_f, in particular, is evaluated from the lognormal distribution of the parameter T_{30}, defined as the time between the 30% and 90% of I_p on the lightning current wave, and assuming $t_f=T_{30}/0.6$, as proposed in [13]. Additionally, we take into account the correlation coefficient between I_p and t_f, and assume it equal to 0.47 [3].

If the distance of the stroke location from the line is beyond the so called lateral distance d_l, the event is considered an indirect flash and the maximum amplitude of the induced overvoltages is computed, otherwise it is considered a direct flash. In this paper we shall make reference to the following expression for the lateral distance [2]

$$d_l(I_p)=\sqrt{r_s^2-(0.9\cdot r_s-h)^2} \quad \text{with } r_s=10\cdot I_p^{0.65} \tag{5}$$

where I_p is the amplitude of the lightning current, r_s is the striking distance to the conductor[1] and h is the conductor height.

Once that the maximum amplitude of the voltage induced along the line is evaluated for each event, the 'classical' flashover rate *vs* CFO voltage curves can be inferred by taking into account the annual flash density N_g and the voltage-time characteristic of the line insulation.

2.3 Additional features

The steady-state voltage at industrial-frequency – taken into account both in the generation procedure of the events and in the overvoltages calculations – is assumed constant,

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[1] Different lateral distance expressions have been proposed in the literature: a sensitivity analysys in this respect has been presented in [14].

due to the high frequency content and the short duration of the induced voltages.

In the generation procedure of the events, uniformly distributed random values of the phase voltage are generated for one of the three phases; the voltages of the two remaining phases are assumed to form, together with the first one, a positive system for each event.

In the overvoltages calculation, the steady-state value of each phase voltage is taken into account by simply adding it to the incident voltage of equation (2). The reason for this is that the current circulating in the line before any lightning event does not effect the amplitude of the induced voltages, and therefore the coupling equations (3) and (4) remain unvaried.

Another additional feature of the proposed procedure, compared to [3], is that it takes into account also the change in the coupling factor among the line conductors and the ground at the location where a flashover occurs. We consider each phase-conductor connected to ground through a resistance R_{gp} at each pole: in normal conditions, the value of R_{gp} is equal to infinite; when a phase-to-ground flashover occurs at a certain pole, the relevant value of R_{gp} is set at a value corresponding to the grounding resistance of the specific pole and the fault impedance. With this simple model, we are able to investigate, in first approximation, up to which extent a flashover of one phase of the line can affect the overvoltages on the other two conductors[2]. The scattered voltage at the points x_p of the phase conductors where the induced voltage exceeds the CFO are calculated by means of

$$\left[u^s(x_p,t)\right]=\left[R_{gp}\right]\cdot\left[(i_{gp})\right]+\left[\int_0^{h}E_z^i(x_p,z,t)dz\right] \qquad (6)$$

where

- $[i_{gp}]$ is the matrix of the induced currents diverted to ground in correspondence of the pole (see Fig. 1);
- $[R_{gp}]$ is the diagonal matrix of the phase-to-ground resistances of the poles.

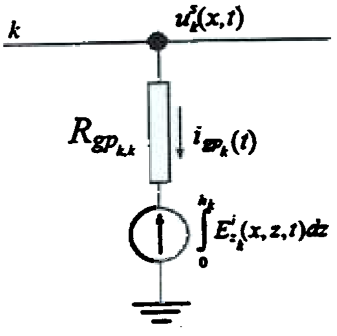

Fig.1 – Pole modeling during k^{th} phase-to-ground flashover of a multi-conductor line illuminated by an external electromagnetic field. (R_{gp} is the grounding resistance of the specific pole).

We consider that an overvoltage causes a flashover when it exceeds the value of 1.5·CFO. The 1.5 factor is an approximation that accounts for the turn up in the insulation volt-time curve, which is the same criterion proposed by the IEEE Guide Std 1410 [2].

III. SOME RESULTS FOR A SINGLE-CONDUCTOR LINE AND THEIR COMPARISON WITH THOSE FROM THE PROCEDURE PROPOSED BY THE IEEE GUIDE STD 1410.

We first briefly summarize the IEEE procedure. For the evaluation of the lightning-induced voltages, the IEEE Guide Std 1410 [2] adopts the simplified formula derived by Rusck in [1] (hereafter called the Rusck formula). Such a formula, inferred by the same Rusck from his more general theory [1], applies to the simple case of a step current and of an infinitely long single-conductor line above a perfectly conducting ground. It gives the maximum value V_{max} (in kV) of the induced overvoltages at the point of the line nearest the stroke location:

$$V_{max}=Z_0\frac{I_p\cdot h}{d}\left(1+1/\sqrt{2}\cdot v\cdot\frac{1}{\sqrt{(1-0.5\cdot v^2)}}\right) \qquad (7)$$

where

$$Z_0=\frac{1}{4\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}=30\Omega \qquad (8)$$

in which I_p is expressed in kA, h, height of the line, is expressed in m, d, distance of the stroke location from the line center, is expressed in m, and v is the ratio between the return-stroke velocity and the velocity of the light. The IEEE Guide disregards the industrial-frequency steady state voltage.

Concerning the statistical procedure used to infer the lightning performance of a distribution line, the IEEE Guide Std 1410 follows the method presented in [13,15], which can be summarized as follows.

The amplitude of the stroke current is varied from 1 to 200 kA in intervals of 1 kA. The number of annual insulation flashovers per km of distribution line F_p is obtained as the summation of the contributions from all intervals considered

$$F_p=2\cdot\sum_{i=1}^{200}\left(d_{max}^i-d_{min}^i\right)\cdot N_g\cdot P_i \qquad (9)$$

where P_i is the probability of current peak I_p to be within interval i^{th}, d^i_{min} is the minimum distance for which lightning will not divert to the line, d^i_{max} is the maximum distance at which the stroke may produce an insulation flashover. Probability P_i is determined as the difference between the probability for current to be equal or larger than the lower limit and the probability for current to reach or exceed the higher limit of the interval i^{th}. Concerning the probabilistic distribution of the lightning current peak, the following expression is adopted [16]

$$P(I_p\geq I_p^*)=\frac{1}{1+(I_p^*/31)^{2.6}} \qquad I_p^*\leq 200kA \qquad (10)$$

The value of d_{min} is equal to the lateral-distance d_l

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[2] It is worth mentioning that more accurate grounding models for the ground resistances can be found in [4].

determined by expression (5). The value of d_{max} is calculated by means of the Rusk formula (7), taking I_p as the lower current limit of the interval and V_{max}=1.5·CFO.

The results for a single-conductor, 10 m high overhead line, according to the IEEE Guide, are shown in Fig. 2 in solid curve. The value of v in (7) is chosen equal to 0.4 and N_g = 1 flash/km²/yr.

We have first verified that our statistical method gives the same results of the IEEE one when the induced voltages are evaluated by using the Rusck formula instead of using the LIOV code, when the same probability distribution of the lightning current, the same values of return-stroke velocity, of line height and of lateral distance expression are assumed, and when the steady-state voltage is disregarded. We do not report our results in Fig. 2 since they do coincide with those relevant to the IEEE Guide.

We have then compared the IEEE results with those obtained by using our procedure (LIOV plus Monte Carlo), assuming a line length wide enough so that beyond such a line length the illumination of the field becomes unimportant [17] (e.g. 2km) with h = 10 m and v = 0.4, as in [2], both for the case of an ideal ground and for the case of a lossy ground (with conductivity = 0.001 S/m). The indirect stroke area around the line is 8 km². They are shown in Fig. 2 in dashed line.

The difference between the results of our method relevant to the case of perfectly conducting ground and those of the IEEE guide can be explained by observing that the simplified Rusck formula applies to the case of a step waveshape for the lightning current [1]. It is worth mentioning that we repeated our computation by setting t_f at 1 μs and keeping it constant, independently of the amplitude I_p of the lightning current, and we found that the two methods predict basically the same results.

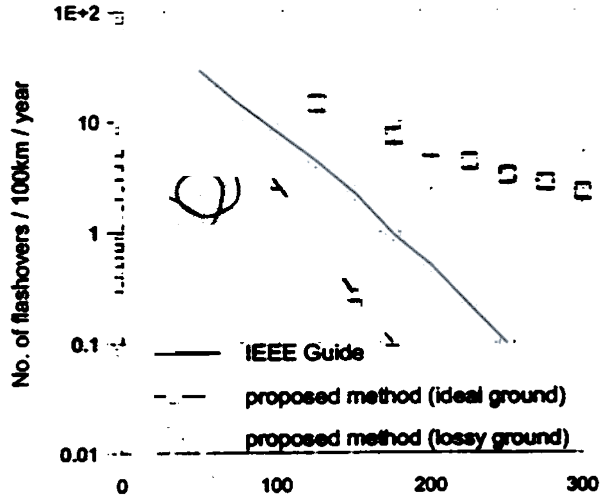

Fig. 2. Comparison between the lightning performances of a single conductor distribution line evaluated by using the IEEE Guide procedure (solid curve) and the proposed one, for two different values of ground conductivity (infinite: triangles-dashed curve, and 0.001 S/m: squares-dashed curve). t_f is lognormally distributed with a median value of 3.83 μs.

The results relevant to the case of lossy ground, clearly, cannot be compared with those of the IEEE Guide. It is interesting to observe, however, how the ground resistivity worsen the line performance: this is due, as earlier shown in [3], to the enhancement of the horizontal component of the electric field due to the soil resistivity [7] and confirms the fundamental importance of an accurate evaluation of the induction mechanism.

IV. APPLICATION OF THE METHOD TO A TYPCAL ITALIAN MV DISTRIBUTION LINE

In this section we evaluate the lightning performance of a typical Italian distribution line (see Fig. 3). We consider a 1.8 km long line matched at both terminations, within an indirect stroke area of 7.6 km². The poles are made out of concrete or steel and are assumed to have a value of grounding resistance R_{gp} in the range 10-100 Ω. The line span between two consecutive poles is 150 m. The amplitude of the r.m.s. value of the steady-state phase-to-phase voltage is 20 kV and the CFO of the line is 125 kV. We assume a ground flash density N_g = 1flash/km²/year.

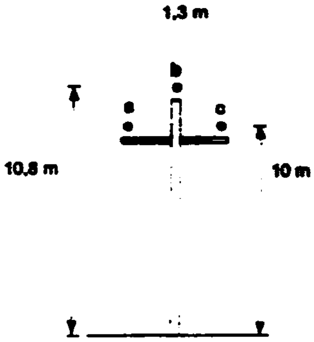

Fig. 3 – Geometrical configuration of an Italian MV line.

We first present the calculation results obtained disregarding the steady state voltage and the CFO of the line. The calculations have been carried out by means of the proposed procedure for two different values of ground conductivity σ_g (infinite and 0.001 S/m), and the results have been scaled to the 'classical' line length of 100 km.

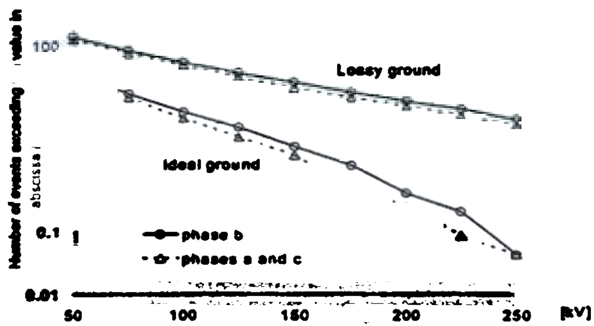

Fig. 4 – Statistical evaluation of lightning induced voltage in the Italian MV line of Fig. 3. Cases for ideal ground and lossy ground (σ_g=0.001 S/m).

They are plot in Fig. 4, which shows the number of events resulting in overvoltages greater than the value reported in abscissa. We observe the larger number of overvoltages at phase b than at phases a and c, due to the larger height of the phase b conductor. Note, again, the increase of the number of induced voltages due poor the soil conductivity.

We now take into account the steady state voltage and the CFO voltage of the line. We consider also the pole grounding resistance at those poles of the line where the CFO is exceeded by the induced overvoltages and consequently a flashover occurs. The LEMP is now calculated assuming two different values for the ground conductivity, namely 0.1S/m and 0.01 S/m.

Fig. 5 shows the voltages induced by a lightning event with I_p = 40 kA, t_f = 3 μs and stroke location equidistant to the line termination, 50 m from the line. The electromagnetic field radiated by lightning is calculated assuming the ground conductivity equal to 0.01 S/m. Also, we assume a phase to ground voltage equal to 16 kV and a resistance R_{gp} of the poles during a phase to ground flashover equal to 10 Ω.

Fig. 5a shows the behavior of the induced voltage amplitude on phase b at the various poles. The flashover of phase b at pole 6 at about 2 μs causes a voltage reduction at the same pole, which propagates in both directions along the line. Fig 5b shows the top view of the three-dimensional plot of Fig. 5a.

In Figs. 6-9 we show the results of the statistical analysis (80000 events overall) carried out on the Italian MV line configuration of Fig. 3, with N_g=1flash/km^2/year, for two different values of ground conductivity, namely 0.1 S/m and 0.01 S/m (electromagnetic field calculation), and of pole grounding resistance, namely 10 and 100 Ω. In particular, they report the expected number of flashovers, distinguishing among one phase to ground, and two or three phases to ground, caused by a single event.

To better assess the importance of taking into account the steady-state voltage in the calculations, in Figs 6-9 we report also the results for the case in which the steady-state voltage is disregarded. In general, the taking into account of the steady-state voltage results in a larger number of flashovers: 1.5 instead of 1.3 in Figs. 6 and 8, 3.7 instead of 3.2 in Figs. 7 and 9.

We can observe the larger number of ground flashovers at phase b than at the two others phases, independently of the steady-state voltage; this is a consequence of the height of phase b, larger than that of the other two phases (see also Fig. 4). The increase of the pole grounding resistance produces, in general, an increase of the number simultaneously faults to ground (two or three phases). The phase where a flashover occurs produces in fact the same shielding effect as a shielding wire; such an effect tends to decrease with the increase of the grounding resistance [20].

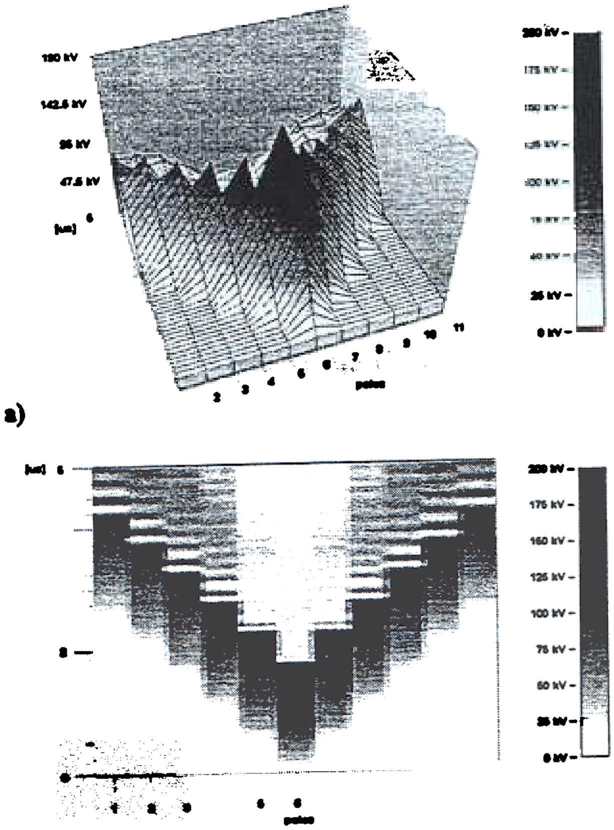

Fig. 5 – Voltage amplitude induced on phase b by a lightning event with I_p = 40 kA, t_f = 3 μs, stroke location equidistant to the line termination, 50 m from the line of Fig. 3. The LEMP is calculated assuming a ground conductivity σ_g=0.01 S/m. The grounding resistance of the poles R_{gp}=10 Ω. a) Three dimensional view of voltages on phase b; b) top view of the three dimensional surface of Fig. 5a.

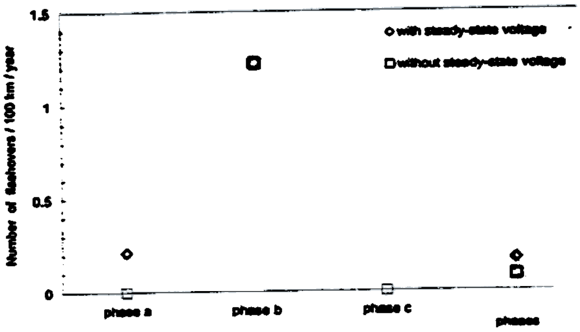

Fig. 6 – Number of flashovers along the line, R_{gp}=10 Ω and σ_g=0.1 S/m.

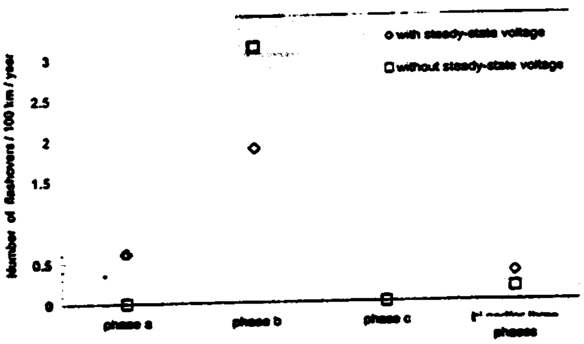

Fig. 7 – Number of flashovers along the line, R_{gp}=10 Ω and σ_g=0.01 S/m.

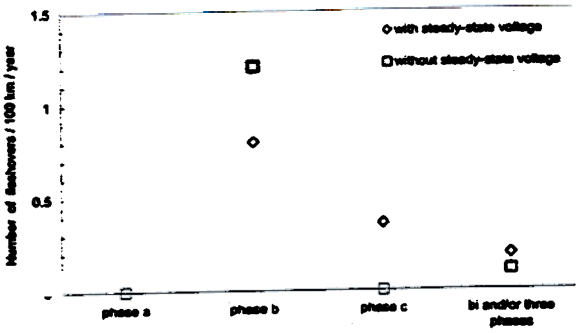

Fig. 8 – Number of flashovers along the line, R_{gp}=100 Ω and σ_g=0.1 S/m.

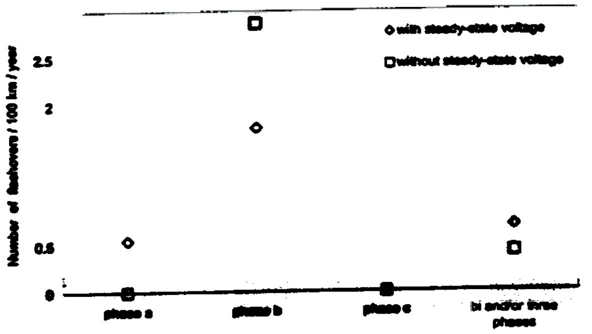

Fig. 9 – Number of flashovers along the line, R_{gp}=100 Ω and σ_g=0.01 S/m.

IV. CONCLUSIONS

The paper has illustrated a procedure based on the Monte Carlo method which allows an improved evaluation of the lightning performance of distribution lines with reference to lightning-induced voltages. Such a procedure makes use of the LIOV code for the calculation of the lightning-induced voltages and of the Monte Carlo method for the statistical evaluation of the line performance.

The procedure has been compared with the one proposed in the IEEE Std 1410-1997 Guide for the same purpose: it has been shown that for those cases for which a comparison is possible (overhead single-wire line above a perfectly conducting ground, step function for the channel base current) the two methods predict basically the same results.

Compared to the IEEE procedure, the proposed one allows to take into account the soil resistivity – which plays a fundamental role in the calculation of the electromagnetic field radiated by lightning that excites the line –, any arbitrary waveshape of the lightning current, the steady-state voltage, the grounding resistance of the line poles.

The methodology has been applied for a first assessment of the lightning performance of a typical Italian distribution line.

Improvements of the procedure here proposed are in progress and focus on

- a more accurate modeling of the pole groundings;
- a better assessment of the expression to be used to evaluate the lateral distance (see [14]);
- the taking into account of the various power components that are typically connected to distribution lines, such as distribution transformers;
- the inclusion of line protection devices, such as surge arresters, for each phase of the line (see [21])

Concerning the last two points, the code resulting from the interface between LIOV and EMTP [22,23] appears a promising tool.

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