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Assessment of the Effects of the Electromagnetic Pulse on the Response of Overhead Distribution Lines to Direct Lightning Strikes

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ABSTRACT In the usual practice, the evaluation of overvoltages due to direct lightning strikes to overhead power lines is focused on the representation of the effects of the lightning current injection, whilst the effects of the coupling between the conductors and the lightning electromagnetic pulse (LEMP) is disregarded. Motivated by recent results obtained for the case of a medium voltage line configuration with a shield wire, this paper extends the analysis to assess the contribution of the LEMP on the lightning performance of an overhead distribution line with and without periodically grounded wires and surge arresters. Moreover, the paper deals with the LEMP effect on the occurrence probability of flashovers on different phases, which is an important information on the service continuity of networks with isolated or compensated neutral earthing. A validation of the results is obtained by comparing the overvoltages calculated by the electromagnetic transient program including the model of the line illuminated by the LEMP and those obtained by a three-dimensional finite difference time-domain approach.

INDEX TERMS Distribution line, direct lightning, lightning electro-magnetic pulse, flashover rate, lightning protection.

NOMENCLATURE

$i(t)$	current waveform at the channel base
$I_0, \tau_1, \tau_2, \eta, n$	Heidler function parameters
I_p, t_f, S_m, t_h	peak value, equivalent front time, maximum steepness, and time to half value of $i(t)$
$v(t)$	voltage across insulators at time t
$D(t)$	value of the flashover model integral at time t
V_0, t_0, k	parameters of the integration model
$DE*$	flashover value of D
F_p	annual number of flashovers
$A, n_{\text{tot}}, n_{\text{d}}$	Monte Carlo events: collecting area, total number and number of direct events causing a flashover.

I. INTRODUCTION

THE assessment of the expected rate of lightning-originate flashovers and damages to the equipment connected to power distribution lines requires considering the effects of both direct and indirect lightning strokes [1]–[4].

Although field observations suggest that many of the lightning-related disturbances occurring in MV-lines are due to lightning striking the ground near the line [1], [5], direct events are possible cause of line faults as well, unless surge arresters (SAs) are regularly installed at close distance [6]–[8]. In several studies e.g., [9], EMTP (electromagnetic transient program) calculation models, in which the lightning strike is represented by an equivalent generator, i.e., a current source in parallel with the wave impedance of the lightning channel [4], [10], are shown to be adequately accurate for reproducing overvoltages originated by direct lightning strikes. This approach, typically adopted for calculating the backflashover rate of transmission lines [11], implies disregarding the effect of the lightning electromagnetic pulse (LEMP) radiated from the lightning channel with respect to that of the current injection.

The results of the recent analysis presented in [12] suggest that the LEMP effect may have an important effect on the lightning performance of distribution lines, especially in presence of periodically grounded wires. The aim of this paper is to extend the results of [12] and to compute the LEMP contribution also in case of a direct strike to the phase conductors of a line not equipped with a shield-wire. The analysis is initially performed by means of time domain comparisons to analyze the polarity and the magnitude of the two contributions (LEMP and current injection) to the total overvoltage. Furthermore, this paper compares the lightning performance against direct strikes of an overhead distribution line with and without grounded shield wires and with and without surge arresters (SAs). The occurrence probability of multi-phase flashovers, i.e., flashovers on insulators of different phases, is also assessed. This is an important information for networks with isolated or compensated neutral earthing, in which flashovers on insulators of the same phase may not require circuit breaker operations if the power-follow current extinguishes spontaneously [6].

Several approaches for calculating the induced voltages on overhead lines have been proposed in the literature e.g., [13]–[21]. In many of these approaches, the calculation of the overvoltages induced by lightning events terminating on the ground or hitting objects close to the line is performed by first evaluating the lightning electromagnetic pulse (LEMP) and then by assessing the line response through the solution of the field-to-line coupling equations [22], within the basic assumption of the transmission line (TL) theory, i.e., by assuming the response of the line is quasi-transverse electromagnetic (quasi-TEM).

Several of the abovementioned calculation methods are conceived to be integrated in EMTP-like simulation environments to assess the effects of lightning strikes on real power systems. The advantages and limits of these models based on circuit theory for lightning surge analysis are discussed in e.g., [23]. Full-wave computational approaches, such as the finite-difference time-domain (FDTD) method, do not require the assumption of TEM response. For the case of 3D structures, such as high voltage line towers [9], [24], it is shown that the non-TEM characteristics may have a significant influence on the overvoltages calculation. A three-dimensional finite difference time-domain (3D-FDTD) that calculates the overvoltages due to direct strikes to transmission lines and substations considering the LEMP effects is presented in [25].

This paper presents the calculation results of the response of a power distribution overhead line to a direct lightning strike, obtained by means of the following methods:

- *FDTD* which intrinsically considers both the effects of the current injection and the LEMP-coupling with the line conductors,
- *EMTP* which simulates the line response assuming the direct strike can be modelled by means of an equivalent current source, thus, neglecting the LEMP effect,
- *LIOV-EMTP* in which the LEMP effect is also taken into account by using the LIOV-EMTP code [26], [27].

Since the use of 3D models requires a significant computational effort that makes them unsuitable for the statistical assessment of the flashover rate for realistic configurations, as in [12], the lightning performance is finally evaluated by means of the latter two aforementioned methods.

The structure of the paper is the following. Section II presents the case study and the calculation method. Section III presents some time domain transient overvoltages due to direct strikes to a line without and with SAs. Section III deals with the assessment of the flashover rate and the occurrence of multi-phase flashovers. Section IV is devoted to the conclusions.

II. CASE STUDY AND OVERVOLTAGE CALCULATION METHODS

The analysis of the LEMP contribution on the overvoltages due to direct strikes is presented for two pole configurations, shown in Fig. 1, having identical geometry of the phase wires, but one equipped with a shield-wire, i.e., the same configuration discussed in [12], and the other one with no shield-wire installed.

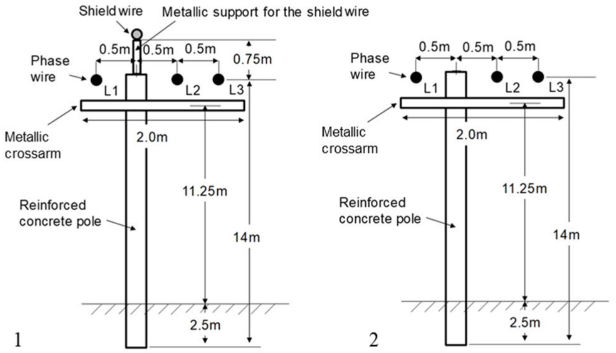

FIGURE 1. **Arrangement of the poles: Configuration 1 – with shield-wire and Configuration 2 – without shield-wire.**

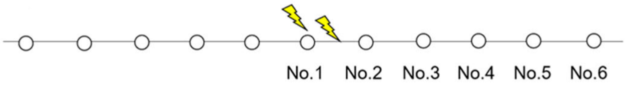

FIGURE 2. **Line topology and lightning strike locations LA at pole No. 1 and LB 20 m away from pole No. 1.**

The case study refers to a 1-km long distribution line with a span length of 40 m. Fig. 2 shows the line topology, the observed pole and location of the considered direct strikes locations.

The voltage at the utility frequency (6.6 kV for the considered line) is disregarded, since it is much smaller than the critical flashover voltage of the insulators.

The analysis presented is limited to negative flashes. In Section III, the time domain voltage transients are calculated for two different channel-base current waveforms, assumed to be representative of a typical first and subsequent negative stroke, respectively.

As mentioned in the Introduction, the overvoltages due to a direct strike can be ascribed to the lightning current injection and to the effect of the LEMP-coupling to the line conductors. In the EMTP calculations, the lightning current injection is modelled by means of an ideal current source. The negative terminal of the current generator is connected to the line conductors (or shield wire for configuration 1), while the positive terminal is grounded. In the FDTD model and in the LEMP calculation of the LIOV-EMTP code, the return stroke is represented by a current distribution along the channel according to the so-called transmission line model [28].

The value of the ground conductivity is 0.01 S/m. The relative permittivity is 10.

In the LIOV-EMTP code, the LEMP and the line response to the external electromagnetic field are calculated by adopting the Agrawal *et al.* LEMP-to-line conductors coupling model [22] and the Cooray-Rubinstein formula [29], [30] to represent the effect of finite ground conductivity on the LEMP propagation. Only the coupling of the LEMP with the horizontal conductors is considered. The strike is considered as a lightning channel very close to the line (10 m far from the line in the calculations presented in this paper). As discussed in [12], this simplifying assumption allows a good compromise between numerical stability and accuracy of the results, assessed with respect to the ones provided by the FDTD model.

The detailed description of the FDTD model, including the domain discretization and the boundaries setup, can be found in [12]. The FDTD model is implemented and solved by using the 3D surge simulation code developed by CRIEPI called Virtual Surge Test Lab (VSTL). The Restructured and Extended Version (VSTL REV) described in [31] and [32], can deal with several important components for lightning surge analysis such as thin wires, SAs, lightning channels, and so forth.

In the EMTP calculations, the pole is represented by a 15 m-long single-conductor lossless constant-parameter line in series to a grounding resistance. According to the experimental results presented in [33] and [34], the pole surge impedance is set to 300 Ω and the grounding resistance is assumed equal to 20 Ω. These assumptions are also supported by the results of step response calculation by means of the FDTD method presented in [35]. The current wave is assumed to propagate along the pole at the speed of light [36]. The soil ionization and the frequency dependence of the grounding electrode are neglected.

The soil resistivity affects the grounding resistance of the poles, the line parameters, and the propagation of the LEMP over the soil. The 20 Ω grounding resistance value of the poles is a reasonable value for the assumed grounding arrangements of the poles and the 0.01-S/m ground conductivity value. As the adopted Cooray-Rubinstein approximation becomes less accurate at very close distance and very low ground conductivities [37], the analysis at higher soil resistivity is outside the scope of this paper.

The insulators are mounted on a metallic crossarm, which is explicitly represented only in the FDTD model. The Integration Model (IM) [38] is used to represent the withstand capabilities of the line insulators and to discriminate between single-phase and multi-phase faults. A flashover occurs if the time integral D of the insulator voltage exceeds a given value DE^*. Integral D is given by the following expression

$$D(t) = \int_{t_0}^{t} [|v(t)| - V_0]^k \, dt \tag{1}$$

where $v(t)$ is the voltage across the pole insulator, V_0 is the minimum voltage to be exceeded before any breakdown process can start, k is a dimensionless factor, and t_0 is the time at which $|v(t)|$ becomes greater than V_0.

The assumed parameters for the IM assumed are: $V_0 = 132$ kV, $k = 1$ and $DE^* = 66$ kVμs. These values have been inferred in [12] on the basis of voltage-time-to-breakdown experimental results for positive polarity standard lightning impulse voltages applied to a 6.6-kV solid core type insulator.

III. TIME DOMAIN TRANSIENTS

In this Section the waveforms of the overvoltages across insulators due to direct strikes on the distribution lines are shown. The aim of the following comparisons is to highlight the polarity and the incidence of the two contributions to the total overvoltage (LEMP and current injection), and to compare the results obtained by the three abovementioned calculation methods. To avoid the occurrence of sharp variations and spikes in the voltage waveforms due to flashovers, in this Section we assume ideal insulators, i.e., characterized by a withstand voltage so high that no flashovers can occur.

Two lightning current waveshapes are considered, corresponding, as above mentioned, to a typical first stroke and subsequent stroke. The current waveforms are modelled by means of Heidler functions [39]:

$$i(t) = \frac{I_0}{\eta} \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} \exp\left(-t/\tau_2\right) \tag{2}$$

where $\eta = e^{(-\tau_1/\tau_2)(\tau_2 n/\tau_1)^{1/n}}$. The values of the Heidler function parameters are reported in TABLE 1; the subsequent stroke is represented by the sum of two functions. All the waveforms refer to the phase 1.

The polarity difference of the LEMP effect in the two cases with and without ground wire is illustrated by Fig. 3 and Fig. 4. For a direct strike to the shield wire (configuration 1 of Fig. 1), Fig. 3 shows the overvoltage across phase-1 insulator

TABLE 1. **Heidler current waveforms parameters.**

Waveform	Heidler function parameters			
	I_0	τ_1	τ_2	n
First	31.1 kA	7.8 µs	97.6 µs	10
Subsequent	10.7 kA	0.25 µs	2.5 µs	2
	6.5 kA	2.1 µs	230 µs	2

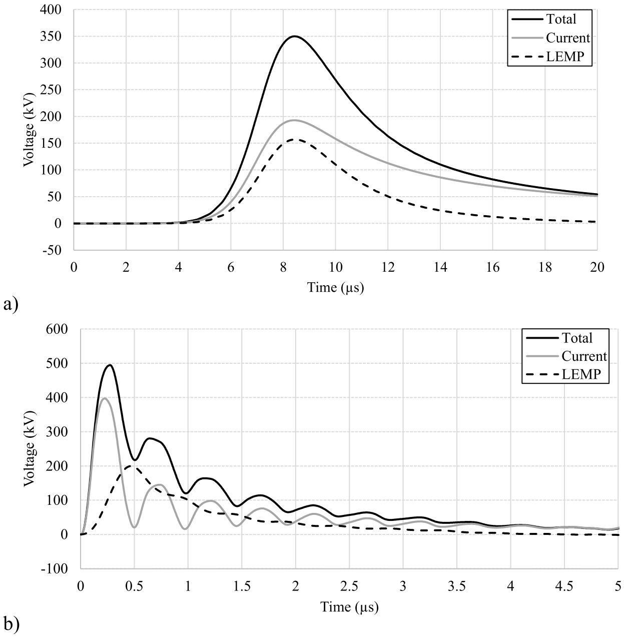

FIGURE 3. **Voltage across an ideal insulator of a pole struck by a first (a) and a subsequent stroke (b) for the line with shield wire (configuration 1, pole No. 1, strike location LA): total voltage, current contribution, and LEMP contribution.**

of the struck pole. The figure includes three curves, all calculated by the LIOV-EMTP model for the strike location LA of Fig. 2 and the current waveshape of a first (Fig. 3.a) and subsequent stroke (Fig. 3.b): the total overvoltage waveform, the component due to the lightning current injection and the one due to the LEMP only. The latter two contributions have the same polarity, therefore the LEMP contribution increases the voltage across the insulators of a line equipped with a shield-wire.

An analogous comparison is shown in Fig. 4 for a direct strike to a line without shield wire (configuration 2 of Fig. 1). In this case, the overvoltage due to the current injection has negative polarity, while the LEMP contribution has positive polarity. Therefore, the LEMP effect slightly reduces the total voltage across phase insulators, but its contribution is less important than for configuration 1, especially for the case of a first stroke (Fig. 4.a).

These considerations are valid also in case of positive strikes. The opposite lightning current polarity would change the polarity of both the injected current and the induced voltages [40].

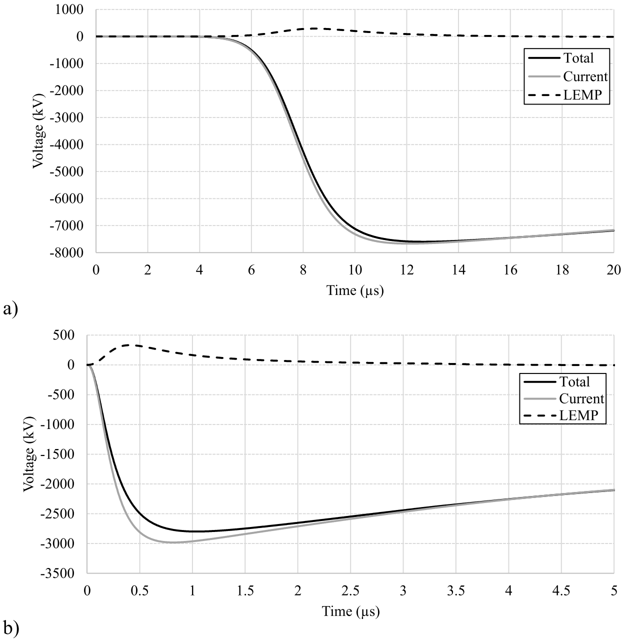

FIGURE 4. **Voltage across an ideal insulator of the pole struck by a first (a) and a subsequent (b) stroke for the line without shield wire (configuration 2, pole No. 1, strike location LA): total voltage, current contribution and LEMP contribution.**

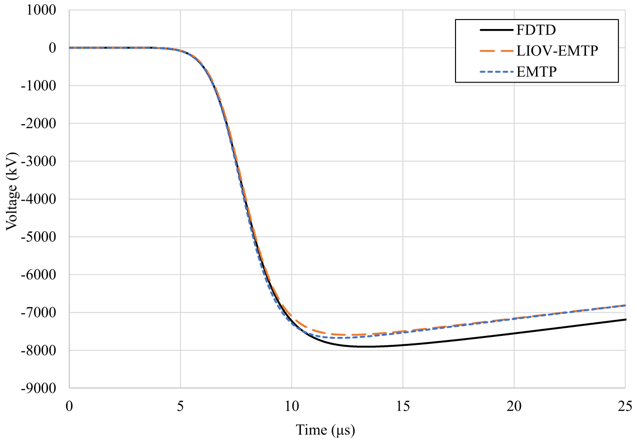

FIGURE 5. **Voltage across an ideal insulator 20 m away from a first stroke (configuration 2, pole No. 1, strike location LB). Comparison between the different models.**

The considerations for the line without shield wire are confirmed by the comparison of the results obtained by using the 3D-FDTD approach, the LIOV-EMTP code, and the EMTP without including the LEMP effect, as shown in the following subsections for the case without and with surge arresters. For all the considered cases, the results obtained by the LIOV-EMTP model are in good agreement with those obtained by means of the FDTD calculations.

A. WITHOUT SURGE ARRESTERS

For the case of a direct strike to pole No. 1 of line configuration 2 and first-stroke current, Fig. 5 shows the voltage

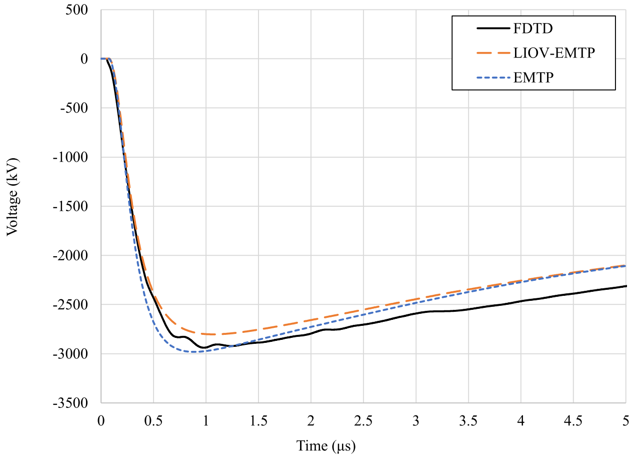

FIGURE 6. **Voltage across an ideal insulator 20 m away from a subsequent stroke (configuration 2, pole No. 1, strike location LB). Comparison between the different models.**

across the insulator 20 m away from the struck pole calculated with the three different methods, namely the FDTD model, the EMTP model with LEMP effect (LIOV-EMTP) and without LEMP (EMTP). Analogous results are reported in Fig. 6 for the subsequent stroke current waveform. As in the previous cases, only the voltages of phase 1 are reported.

For the case without surge arresters, there are no significant differences between the curves. The current injection without any protection against surges causes a very large overvoltage. Indeed, without surge arresters, it is expected that insulation flashovers occur along the line. As already mentioned, flashovers are not considered in these comparisons.

B. WITH SURGE ARRESTERS

A set of three SAs installed every 200 m are considered, as shown in Fig. 7. SAs are represented by means of nonlinear resistors in all EMTP and FDTD models. The voltage-current characteristic of the installed SAs is the same adopted in [12]. As done so far, only the voltages of phase 1 are shown.

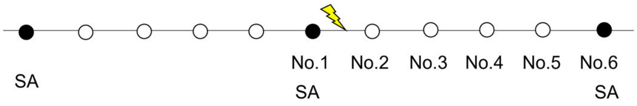

FIGURE 7. **Locations of the installed SAs and lightning strike.**

Fig. 8 shows the comparison of the overvoltage on phase 1 of pole No. 2 calculated with the three different models for line configuration 2 and the first-stroke current waveform. The peak value of the overvoltage calculated by neglecting the LEMP contribution (EMTP) is slightly overestimated. Fig. 9 shows the comparison between the overvoltage calculated at pole No. 4.

The comparisons repeated for the case of the subsequent-stroke current waveform are shown in Fig. 10 and Fig. 11, for the case of pole No. 2 and No. 4, respectively. In both cases, the maximum peak amplitude of the overvoltage calculated with LIOV-EMTP is close to the one estimated by the FDTD method. The subsequent peaks, due to reflections between SAs, appear to be less damped for the waveforms estimated by means of the two EMTP models likely due to the representation of the ground impedance of the pole and the line surge-propagation losses. In both the EMTP and LIOV-EMTP simulations, the grounding is modelled by means of a simple resistor and the transient ground resistance of the line is deliberately disregarded (although it may have some effects as shown in [41]).

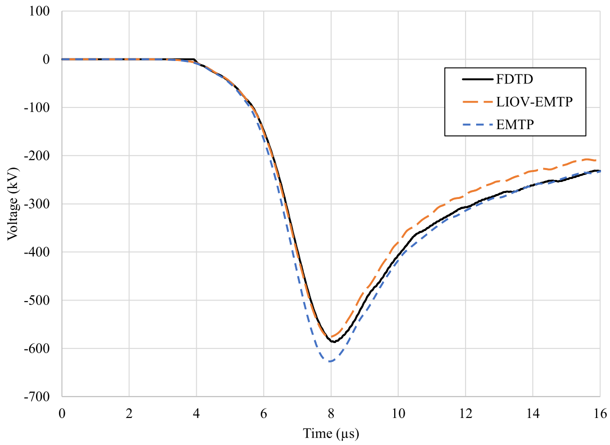

FIGURE 8. **Voltage across an ideal insulator 20 m away from a first stroke on the line without shield wire, 40 m from SA (configuration 2, pole No. 2). Comparison between the different models.**

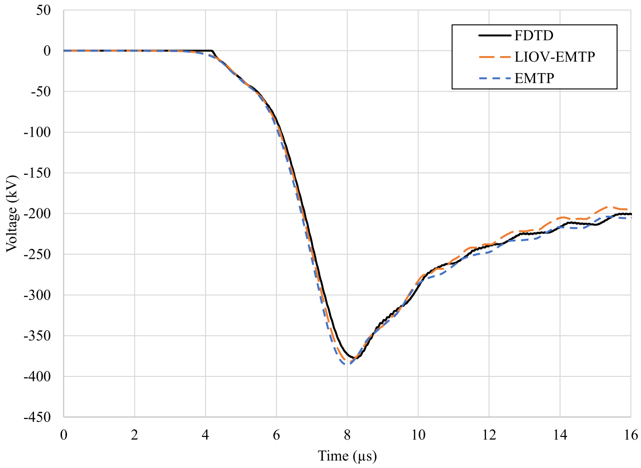

FIGURE 9. **Voltage across an ideal insulator 100 m away from a first stroke on the line without shield wire, 80 m and 120 m away from SAs, (configuration 2, pole No. 4). Comparison between the different models.**

The computational time required to obtain the results of Fig. 10 or Fig. 11 by using the FDTD method (207,704 time steps, 0.125m-2m cell size, non-uniform cell) is about 10 hours. The calculations have been obtained by a desktop PC equipped with an Intel Xenon 3.5 GHz CPU with 32 GB of RAM. The computational time required for a LIOV-EMTP simulation is about 15 s, for an observed time window of 16 μs by using a spatial discretization of 2 m (6.67 ns) in the 1D-FDTD of the LIOV code. The computational time drops to about 1.5 s if the LEMP is neglected.

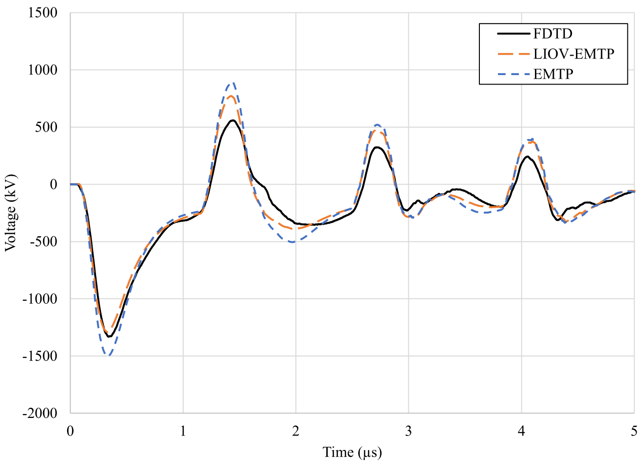

FIGURE 10. Voltage across an ideal insulator 20 m away from a subsequent stroke on phase 1 and 40 m from SA, without shield wire (configuration 2, pole No. 2). Comparison between the different models.

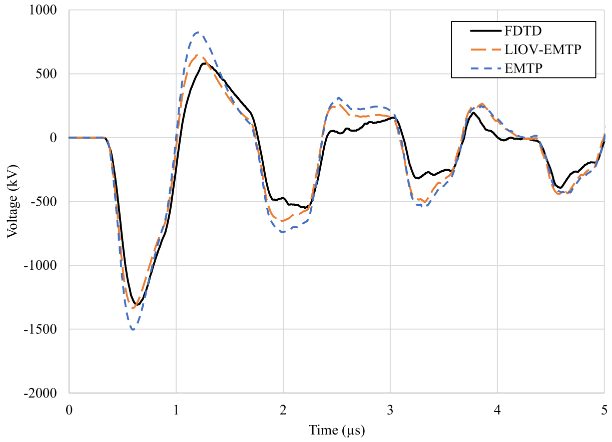

FIGURE 11. Voltage across an ideal insulator 100 m away from a subsequent stroke on phase 1, at 80 m and 120 m away from SAs, without shield wire (configuration 2, pole No. 4). Comparison between the different models.

IV. STATISTICAL ASSESSMENT OF THE LIGHTNING PERFORMANCE

This Section is devoted to the calculation of the lightning performance of the line i.e., the estimation of the expected annual number of overvoltages able to cause insulator flashovers.

The calculation is carried out by using a procedure based on the Monte Carlo method [42]. The procedure begins with the generation of a large number n_{tot} of lightning events, each representing a negative first stroke, which current is modelled by a Heidler function. As the Heidler function requires four parameters to be defined (namely, current peak amplitude I_p, equivalent front time t_f, maximum front steepness S_m and wave-tail time to half value t_h, [43]) the procedure described in [44] is adopted for the generation of the multivariate log-normal distribution of the lightning current parameters. The complete set of the adopted parameter values is reported in TABLE 2 and TABLE 3, and are taken by [45]. For the sake of comparison, the parameters are the same adopted for the statistical calculations performed in [12].

TABLE 2. Parameters of the log-normal distributions for negative downward first strokes [45].

Parameter	Median value	**Standard deviation** of the parameter logarithm (base 10)
I_p	30 kA	0.26
t_f	3.83 µs	0.31
S_m	12 kA/µs	0.26
t_h	75 µs	0.26

TABLE 3. Correlation coefficients between parameters for negative downward first strokes [45].

Parameter	I_p	t_f	S_m	t_h
t_f	0.37	1		
S_m	0.36	-0.21	1	
t_h	0.56	0.33	0.1	1

The location of the n_{tot} events is uniformly distributed in an area A whose borders are 500 m far from a 2-km long line with matched terminations, as shown in Fig. 12, in which direct events are plotted in red and indirect ones in blue. As in [12], due to the symmetry of the geometry, the location of all the generated events ($n_{tot} = 20000$ events) are concentrated in an area A of 0.4 km^2 around the pole at the midpoint of the line.

The direct and indirect events are singled-out by employing the electro-geometric model (EGM) adopted in [1]. For configuration 1, by applying the EGM considering the height of the shield wire, the number of directs events is 2450. For configuration 2, by considering the height of the pole, the number of direct events is 2396. Shielding failure is neglected for configuration 1, so all the flashes are assumed to hit the shield wire. For configuration 2, the direct events are uniformly distributed among the three phase conductors, neglecting direct strikes to the top of the poles.

For each Monte Carlo event, a LIOV-EMTP simulation is performed to calculate the response of line and the possible occurrence of flashovers according to the adopted model IM.

The annual numbers of direct strikes expected to cause a flashover F_p is given by

$$F_p = \frac{n_d}{n_{tot}} A\, N_g \tag{3}$$

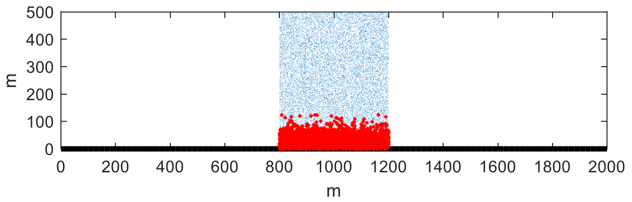

FIGURE 12. **Top view of the stroke locations of the Monte Carlo events. Direct events in red, indirect in blue. The 2-km long line is located along the x axis.**

where n_d are the number of direct events able to cause a flashover and N_g is the annual ground flash density, assumed equal to 1 flash/km^2/yr.

The following cases are simulated for both configurations 1 and configuration 2 of Fig. 2:

- case A: without SAs;
- case B: SAs installed every 400 m;
- case C: SAs installed every 200 m.

The results of the Monte Carlo procedure in terms of yearly single-phase and multi-phase flashover rate are reported in TABLE 4 and TABLE 5 for configuration 1 and configuration 2, respectively.

As a confirmation of the analysis provided in [12], the LEMP contribution increases the annual number of flashovers for configuration 1.

According to [1], for a line such as the one of configuration 2, the expected number of direct lightning flashes to the phase conductors is approximately 12 flashes/100 km/yr. Since almost all these events are expected to cause at least one insulation flashover, the enhancement due to the LEMP effect is not appreciable for configuration 2, as can be seen by the first two columns of TABLE 5. The LEMP contribution, instead, increases the annual number of multi-phase flashovers.

Note that the first phase that undergoes a flashover reduces the overvoltages on the other wires likewise a shield wire. Therefore, multi-phase flashover rates are lower than single phase flashover rates also without shield wire.

TABLE 4. **Calculated flashover rate due to direct events for line config. 1.**

Case	Single-phase (number/100km/yr)		Multi-phase (number/100km/yr)	
	without LEMP	with LEMP	without LEMP	with LEMP
A (without SAs)	6.7	11.3	3.7	9.8
B (with SAs every 400 m)	5.8	8.1	3.2	6.1
C (with SAs every 200 m)	4.3	5.4	2.3	3.7

As an illustrative example, let us consider configuration 2, case B, and one of the generated Monte Carlo events corresponding to a direct strike to phase 1 of the pole located at $x = 1120$ m. The specific values of the Heidler function parameters are $I_0 = 18.4$ kA, $\tau_1 = 0.703\ \mu s$, $\tau_2 = 60.1\ \mu s$, $n = 2$. Fig. 13 shows the plot of the maximum amplitude (absolute value) of the overvoltages across the phase insulators.

TABLE 5. **Calculated flashover rate due to direct events for line config. 2.**

Case	Single-phase (number/100km/yr)		Multi-phase (number/100km/yr)	
	without LEMP	with LEMP	without LEMP	with LEMP
A (without SAs)	12.0	12.0	6.0	10.8
B (with SAs every 400 m)	12.0	12.0	4.7	7.0
C (with SAs every 200 m)	12.0	12.0	4.1	5.2

By neglecting the LEMP contribution, Fig. 13 shows that all the insulators of the poles between the surge arresters, installed at $x = 1000$ m and $x = 1400$ m, experience a flashover on phase-1 only. By considering the LEMP effect, Fig. 14 shows that flashovers also occur on phase 2 and 3 of the struck pole.

The corresponding time domain waveforms of the voltages across insulators of the struck pole, calculated disregarding and considering the LEMP effect, are shown in Fig. 15.a and in Fig. 15.b, respectively.

Before any flashover occurs, the polarity of the three phase voltages is negative. After a flashover occurs in phase 1, the polarity of the voltages across the other insulators suddenly turns from negative to positive. In case the LEMP contribution is neglected, the overvoltages across insulators of phase 2 and 3 in Fig. 15.a are not able to cause additional flashovers. After the flashover on phase-1 insulator, the LEMP contribution has the same polarity of the voltages across phase 2 and 3 insulators, and therefore enhance them. In fact, the overvoltage peak on phase 3 reaches about 600 kV, as shown in Fig. 15.b, larger than in the previous case. Eventually, phase-3 insulator flashover occurs at about 0.6 μs, and phase-2 insulators flashes shortly afterwards.

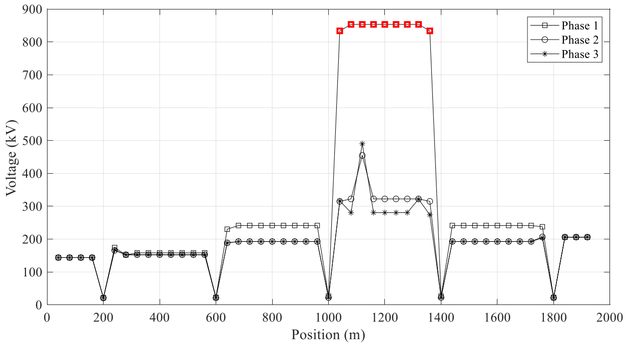

FIGURE 13. **Maximum amplitude (absolute value) of the overvoltages across the phase insulators along the line calculated without LEMP. The overvoltages on poles that experience a flashover are indicated with a red mark.**

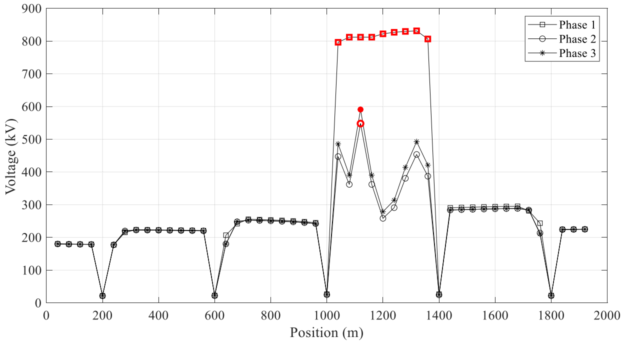

FIGURE 14. **Maximum amplitude (absolute value) of the overvoltages across the phase insulators along the line calculated with LEMP. The overvoltages on poles that experience a flashover are indicated with a red mark.**

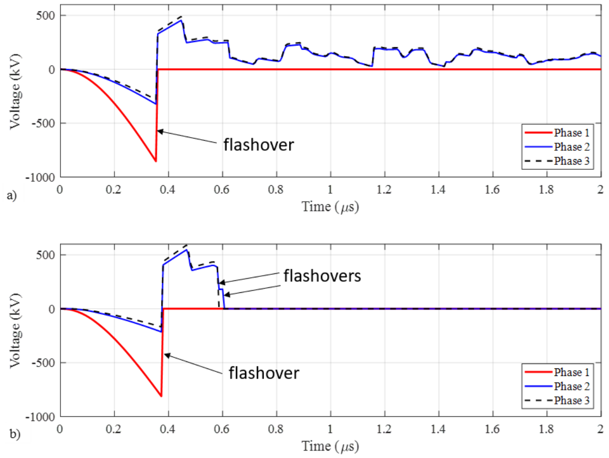

FIGURE 15. **Comparison of the overvoltages across the phase insulators of the pole located at x = 1120 m calculated without LEMP (a) and with LEMP (b).**

V. CONCLUSION

The paper focuses on the assessment of the effects of the lightning electromagnetic pulse on the overvoltages due to direct strikes to power distribution overhead lines. Usually, these effects are not considered in the calculation of the lightning performance. As a confirmation of recent results for the case of a line equipped with a shield wire, when the LEMP effect is taken into consideration, the annual number of expected flashovers increases also in the presence of surge arresters along the line.

The new findings of the presented analysis, carried out by using both EMTP and 3D-FDTD models, is the significant increase of the expected number of multi-phase flashovers, i.e., direct strikes events that cause flashovers in different phase conductors. This occurs also for the considered line configuration without shield wire and allows to obtain a more consistent estimation of the rate of voltage interruptions in distribution networks with isolated or compensated neutral earthing.

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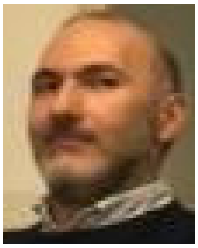

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