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LEMP and ground conductivity impact on the direct lightning performance of a medium-voltage line

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ABSTRACT

In medium-voltage distribution lines equipped with a multi-grounded shield wire and with surge arresters installed along the line at relatively short intervals, lightning outages associated with indirect lightning are less frequent than those associated with direct ones. The protection for this type of distribution lines is therefore dependent on the response to direct strikes. This paper presents and analyses the response to direct lightning overvoltages of lines of such a type located over a lossy soil considering the influence of the lightning electro-magnetic pulse (LEMP), which is typically disregarded in the calculation of overvoltages due to direct strikes. The calculation results, performed by means of a three-dimensional finite-difference time domain (3D-FDTD) method and of the LIOV-EMTP code, indicate that the voltage across the insulator is enhanced by LEMP effects. In addition, it is shown that the enhancement due to the LEMP increases with the increase of the soil conductivity value. The modeling of the LEMP effects is therefore important for the accurate assessment of the lightning performance of medium-voltage distribution lines of the type considered in this paper, even when direct strikes are considered.

1. Introduction

In general, lightning flashover on medium-voltage distribution lines can be caused by both indirect and direct strikes. For lines requiring superior protection, such as typical 6.6-kV medium-voltage (MV) distribution lines in Japan, surge arresters (SAs) are installed at relatively short intervals. These lines experience few lightning faults associated with indirect strikes [1]. The annual number of expected lightning-originated faults, i.e., the lightning performance, is mostly determined by direct lightning events.

For the assessment of the direct lightning performance, circuit-theory-based electromagnetic transient programs, such as EMTP or ATP, are widely used [2–4]. A direct strike on the distribution line is typically represented by a lumped-current source in parallel with a resistance, and the influence of the electromagnetic field associated with the return-stroke current, namely the lightning electromagnetic pulse (LEMP), is typically disregarded.

However, according to recent studies presented by the authors in [5, 6], overvoltages induced by the LEMP may significantly affect the direct lightning performance of some type of MV distribution lines, with specific reference to those equipped with a shield wire. The conclusions of the analysis are supported by the close agreement between the results obtained by means of two different approaches: the three-dimensional finite difference time domain (3D-FDTD) method described in [7,8] and the LIOV-EMTP code described in [9,10].

This paper extends the previous analysis, focusing on the LEMP influence for lines over lossy soils, assuming different values of soil conductivity. The soil finite conductivity has two main effects on the direct lightning voltages: it modifies the LEMP and causes a potential rise in the ground electrodes. As in the previous studies [5, 6], these effects are quantified through the calculation results obtained by both the 3D-FDTD method and the LIOV-EMTP code. Furthermore, the statistical estimation of the critical flashover current values and flashover probability for different soil conductivities and lightning current waveforms is performed, with and without considering the LEMP effects. The flashover occurrence is inferred by using the integral model obtained through the experimental voltage time (*V*-*t*) characteristics of the insulators.

The structure of the paper is the following. Section 2 describes both

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the FDTD and the LIOV-EMTP models of the considered MV line and the adopted assumptions. Section 3 shows the influence of ground conductivity on the overvoltage waveforms considering the LEMP effect. Section 4 presents the statistical estimation of the critical flashover currents and flashover probability for different soil conductivity values and for different lightning current waveforms. Section 5 is devoted to the conclusions.

2. Calculation models

2.1. 3-D FDTD method

The 3-D FDTD simulations are carried out by using the Virtual Surge Test Lab. Restructured and Extended Version (VSTL REV) [7, 8] by Central Research Institute of Electric Power Industry (CRIEPI). VSTL REV can represent thin wires [11–13], surge arresters [14], and the lightning channel.

Fig. 1 shows the considered configuration of a 1-km long 6.6-kV distribution line equipped with a shield-wire. It is the same configuration adopted in [5, 6]. The distribution line is composed of a three-phase conductor and a shield wire supported by concrete poles. In case of direct lightning strikes, the reinforcing bars inside concrete poles behave as down conductors and grounding electrodes [15, 16]. The shield wire is assumed to be grounded at each pole through the reinforcing bars. The specifications of the distribution line and reinforced concrete poles are given in Table 1. The insulating cover of phase conductors is disregarded.

To avoid contamination by reflected waves from the external surfaces, the dimensions of the analysis space is set to 1000 $m \times 400$ $m \times 1000$ m and all the external surfaces are treated as Liao's absorbing boundaries of the second order [17]. Both ends of each conductor are connected directly to the external surfaces. The cell size around the poles and conductors is set to 0.125 m. The other cells have gradually larger dimensions moving away from poles and conductors to reduce the calculation time and required memory capacity. The sizes of these cells ranged from 0.5 m to 2.0 m. The bottom space with a thickness of 30 m represents the soil. The considered soil conductivity values varied from 0.01S/m to 0.001 S/m. The relative permittivity of the soil is set to 10.

The transmission-line (TL) return-stroke model is used to represent the spatial–temporal distribution of the current along a straight vertical lightning channel connected to the top of a pole (the most frequent point of attachment for direct lightning [18]). The assumed return stroke velocity is set to one-third of the speed of light and the return stroke channel is assumed to be vertical.

The voltage at the utility frequency is not considered, for the sake of simplicity, as typically assumed in studies of this type.

Table 1
Specifications of the distribution lines and the concrete pole.

Item	Specification	
Distribution lines		
Shield wire	Steel wire 22 mm^2	
	Diameter	6.0 mm
Phase conductor	XLPE insulated copper wire 80 mm^2	
	Diameter	11.6 mm
Reinforced concrete pole		
Concrete pole	Length	14.0 m
	Diameter	250 mm
Metal for supporting the shield wire	Length	0.75 m
	Diameter	100 mm
Cross arm	Length	1.5 m
	Diameter	100 mm

2.2. LIOV-EMTP

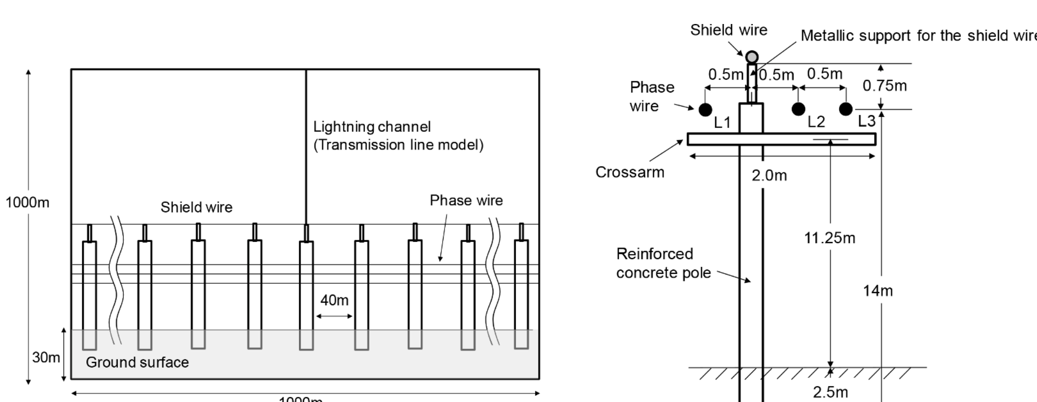
The same line configuration is also represented by means of a model implemented in the EMTP simulation environment by using the LIOV toolbox.

The so-called LIOV line includes the LEMP to transmission line coupling model [19] in the transmission line equations solved by means of a one-dimensional finite difference time domain (1D-FDTD) technique. Both ends of the line are terminated with the surge impedance matrix to prevent reflection of traveling waves.

The lateral distance between the channel and the conductor is zero for direct strikes. However, for the LEMP-to-line coupling solution, the LIOV code solves the transmission line equations by means of a one-dimensional finite difference time domain (1D-FDTD) technique where the LEMP components should be calculated at each spatial discretization. The spatial discretization, correlated with the time step, cannot be larger than the distance between any point of the line and the lightning cannel. As a compromise between accuracy and computational effort, such a distance is chosen equal to 10 m. Notwithstanding this approximation, the results of 3D-FDTD method, for which such an approximation is not necessary, and LIOV-EMTP code are in good agreement, as shown in [5, 6]. The 1D-FDTD time step is set to 6.67 ns.

The concrete pole including the metallic support for the shield wire is modeled by a 15 m-long single-conductor lossless constant-parameter line connected to a grounding resistance in series. The concrete pole surge impedance value is set to 300 Ω according to the results of a step response calculation carried out by using of the 3-D FDTD method [20]. The cross arm is not modeled due to its small dimension.

The grounding resistance of the concrete pole R depends on the soil conductivity [15]:



(a) Side view of the analysis space. (b) Configuration of a pole

Fig. 1. 3-D FDTD model of the distribution line. (a) Side view of the analysis space. (b) Configuration of a pole.

$$R = \frac{\rho}{2\pi l}\ln\left(1 + \frac{l}{r(i)}\right) \tag{1}$$

where l is the length of the concrete pole in soil, ρ is the soil resistivity, and r is the equivalent radius of a grounding electrode that depends on the impulsive current i. According to the Liew and Darveniza model of the soil ionization zone [15, 21], r can be obtained by:

$$r(i) = \frac{l}{2}\left(-1 + \sqrt{1 + \frac{2\rho i}{\pi l^2 E_c}}\right) \tag{2}$$

where E_c is the critical electric field strength for soil ionization initiation.

Due the limited size of the reinforced concrete pole grounding (the same considered in [23]), the effects of the dynamic dependence on the impulsive current waveshape and of the frequency dependent soil parameters are neglected. E_c is taken equal to 400 kV/m, as recommended by CIGRE [22]. The relationship between grounding resistance R and the current amplitude calculated as a function of the ground conductivity is shown in Fig. 2.

The direct lightning strike is represented by a lumped current source connected to the top of the pole. The return stroke velocity and the relative permittivity of the soil are the same as those adopted in the 3-D FDTD method model.

3. Finite ground conductivity and LEMP effects on direct lightning overvoltages

This Section presents the calculated waveforms of the overvoltages across insulators due to direct lightning on the distribution lines assuming the insulators as ideal, i.e., with a withstand voltage so high that no flashovers can occur.

The results are divided in two groups: those obtained without the presence of surge arresters (SAs), and those obtained by considering the presence of SAs installed at poles along the line.

Two lightning current waveshapes are considered: one corresponding to a typical first stroke and the other to a subsequent stroke. The current waveforms are represented by one or the summation of two Heidler functions [24]:

$$i(t) = \frac{I_o}{\eta}\frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n}\exp(t/\tau_2) \tag{3}$$

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 2. All the overvoltage waveforms refer to the phase conductor indicated as L1 in Fig. 1b.

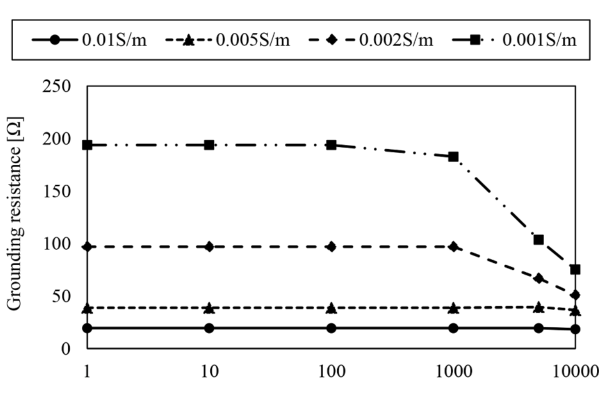


Fig. 2. Current dependence of the grounding resistance of the concrete pole for different values of the soil conductivity.

Table 2
Heidler current waveforms parameters.

Waveform	Heidler function parameters			
	I_0	τ_1	τ_2	n
First	28 kA	1.8 μs	95.0 μs	2
Subsequent	10.7 kA	0.25 μs	2.5 μs	2
	6.5 kA	2.1 μs	230 μs	2

3.1. Without SAs

Figs. 3 and 4 show the voltage across the insulator at the struck pole for the first and subsequent stroke waveforms, respectively, and for different values of ground conductivity. The results of the FDTD method (Figs. 3a and 4a), which intrinsically considers both the effects of the current injection and the LEMP, are much larger than that of EMTP (Figs. 3b and 4b), if the effects of the LEMP are neglected. Instead, the results of the FDTD and the LIOV-EMTP models considering the LEMP effect (Figs. 3c and 4c) show good agreement.

As described in [5], when LEMP is considered, an overvoltage of opposite polarity with respect to the ground potential rise appears on the phase conductors, which enhances the voltage across the insulator.

The comparison demonstrates that the adopted LIOV-EMTP model provides very similar results to the more computationally demanding 3-D FDTD model, for the evaluation of overvoltages due to direct lightning considering LEMP effect in the considered line configuration.

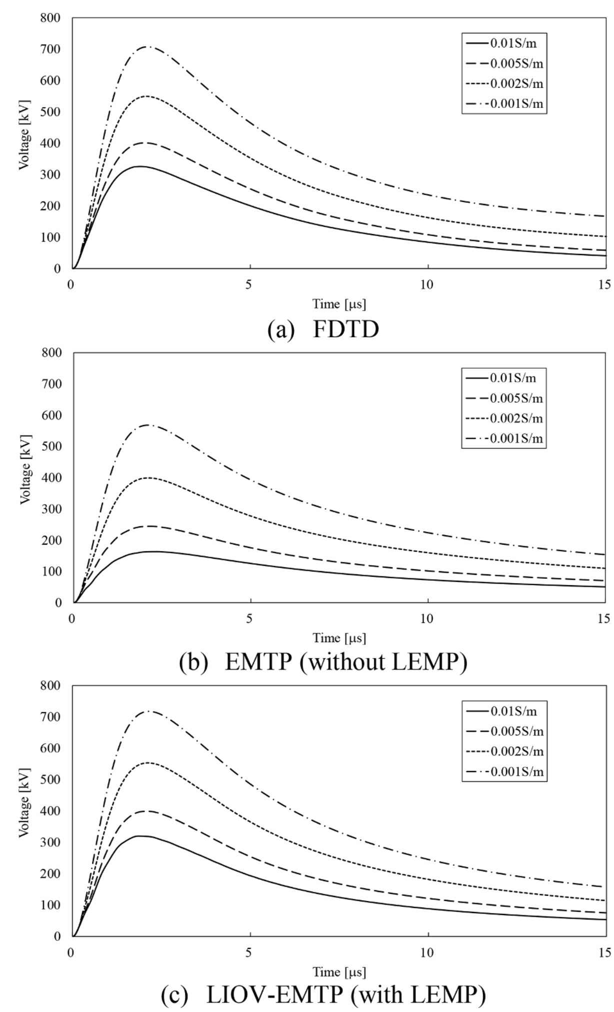


Fig. 3. Comparison of the voltages across the insulator at the struck pole (for the case without SAs) for different ground conductivity values – First stroke.

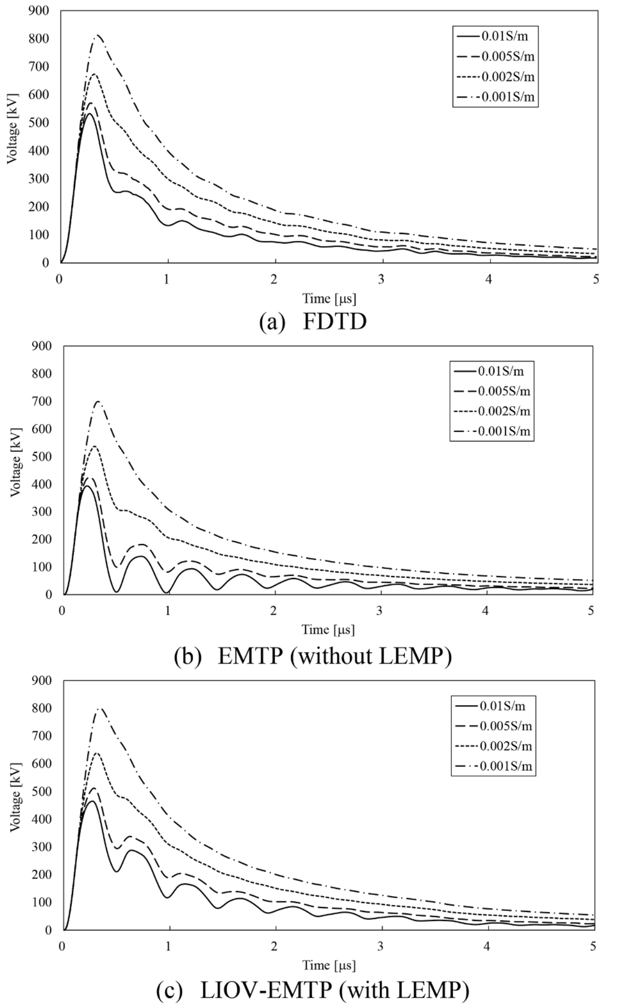


Fig. 4. Comparison of the voltages across the insulator at the struck pole (for the case without SAs) for different ground conductivity values – Subsequent stroke.

Fig. 5 shows the enhancement of the voltage amplitude across the insulator considering the LEMP with respect to the case without LEMP for different values of the ground conductivity. For the first-stroke waveform, the higher the soil conductivity, the higher the ratio. In the case of the subsequent-stroke waveform, characterized by a steeper wavefront than the first-stroke one, the ratio of the voltage peaks with and without LEMP is almost independent of the ground conductivity value and lower than those calculated for the first stroke. For the case of subsequent-stroke waveform and low value of the conductivity soil, the contribution of the ground potential rise to the voltage across the insulator is dominant and the ratio approaches 1.

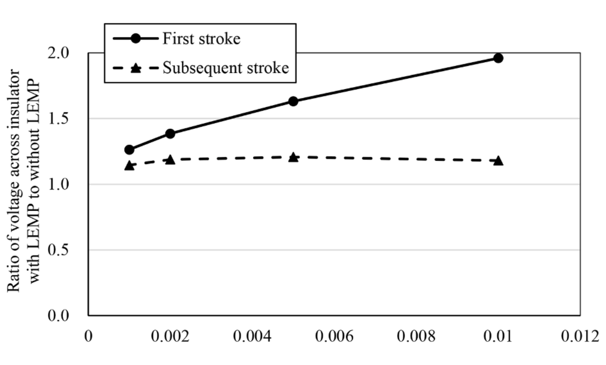


Fig. 5. Ratio between the peak values of the voltages across the insulator calculated by using the LIOV-EMTP model considering LEMP and without considering LEMP, for the case without SAs.

3.2. *With SAs*

Fig. 6 shows the configuration of the line where SAs are installed at five spans interval (i.e., every 200 m). Fig. 7 shows the *V-I* characteristics of the SA.

As the influence of the LEMP can be neglected when lightning hit a pole with SAs [5], we consider the case of a direct lightning to a pole without SAs as shown in Fig. 5. For the sake of simplicity, the reinforced bar of concrete pole is assumed as the grounding electrode of SAs (as sometimes adopted in practice to reduce the construction cost of grounding electrode [25, 26]), modeled according to Eqs. (1) and (2).

Fig. 8 and 9 show the voltage across the insulator at the struck pole for different values of the ground conductivity. The results of the FDTD method and the LIOV-EMTP considering the LEMP are in good agreement. Instead, without considering the LEMP effect, the voltages across the insulators are slightly smaller than those obtained by using the other two methods.

Fig. 10 shows the ratio of the peak voltages across the insulator voltage considering the LEMP with respect to the case without LEMP for the case with SAs. The LEMP effect enhances the insulator voltage at the struck pole, although this impact is smaller than in the case without SAs shown in Fig. 5.

4. Critical flashover current and flashover probability for different soil conductivity values and current waveforms

An evaluation of the LEMP effect on the direct lightning performance is provided by the critical flashover current for different striking points, ground conductivity value and current waveforms. The analysis is focused to MV networks operated with ungrounded or compensated neutral (typical in, e.g., Japan and Italy), where lightning outages typically occur due to short circuits caused by multi-phase flashover [1]. Therefore, critical multi-phase flashover current values are calculated.

4.1. *Calculation procedure*

The critical flashover current for each lightning striking point is evaluated by means of the LIOV-EMTP code. The FDTD method is not suitable for statistical analyses owing to the long calculation time. The following two cases are considered:

Case A – line with shield wire only

Case B – line with shield wire and SAs located at intervals of 200 m.

The assumed waveshapes of the lightning current are the same of Section 3 and the channel impedance is assumed to be 1 kΩ.

The insulator flashover is represented by ideal switches which closes according to the Integration Model (IM) [27]. According to this model, a flashover occurs if the time integral *D* of the insulator voltage exceeds a given value *DE*. Integral *D* is given by the following equation.

$$D = \int_{t_0}^{t} (|V(t)| - V_0)^k dt \tag{4}$$

where $V(t)$ is the voltage on the insulator, V_0 is the minimum voltage to be exceeded before any flashover process can start, k is a dimensionless factor, and t_0 is the time at which $|V(t)|$ exceeds V_0. The parameters for the IM assumed in this paper are: V_0 =131.1 kV, $k = 1$ and $DE = 61.1$ kVμs. These values are inferred from the experimental results of [28] obtained for positive polarity standard lightning impulse voltages applied to a 6.6-kV solid core insulator. Fig. 11 shows the comparison between the measured *V-t* characteristic and the one obtained by the adopted IM representation.

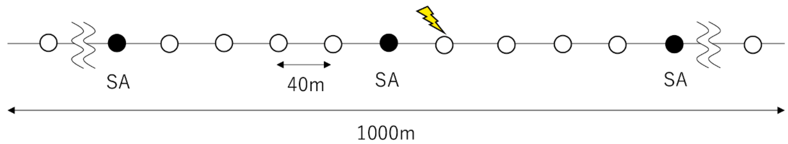


Fig. 6. Location of the installed SAs and considered strike point.

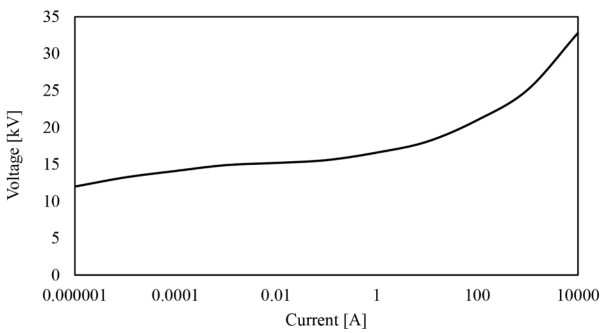


Fig. 7. *V-I* characteristics of typical 6.6 kV surge arrester.

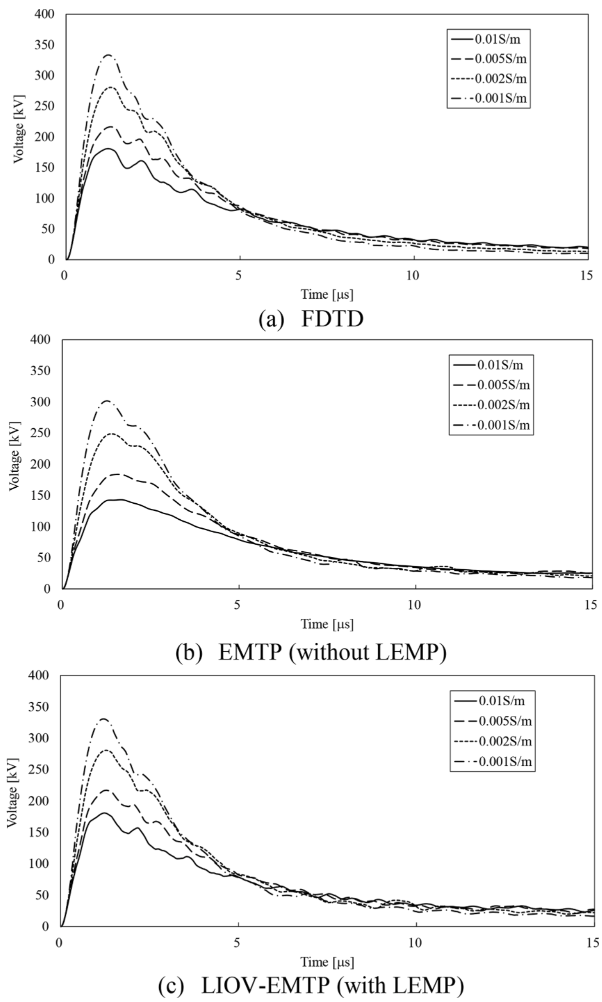


Fig. 8. Comparison of the voltages across the insulator at the struck pole (for the case with SAs) for different ground conductivity values- First stroke.

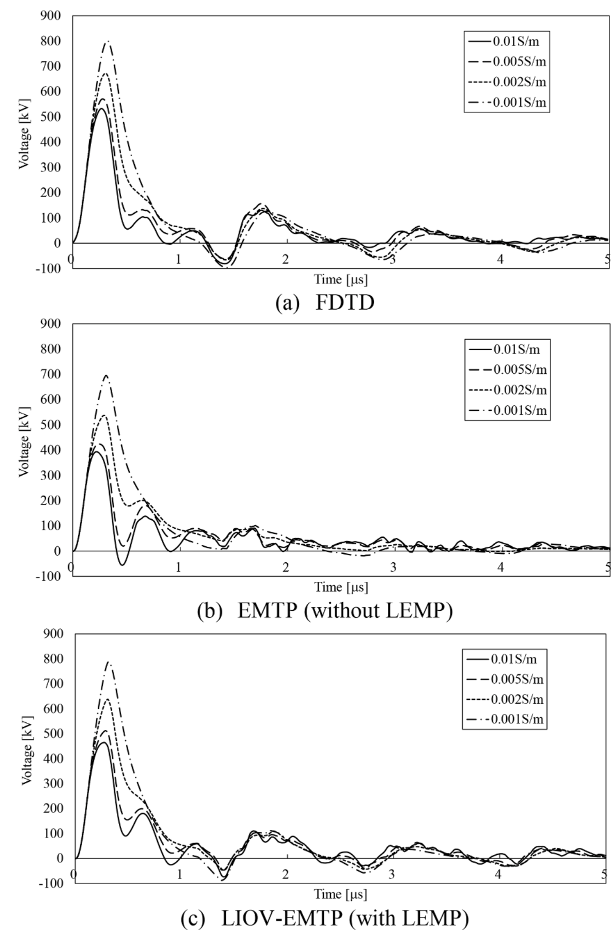


Fig. 9. Comparison of the voltages across the insulator at the struck pole (for the case with SAs) for different ground conductivity values- Subsequent stroke.

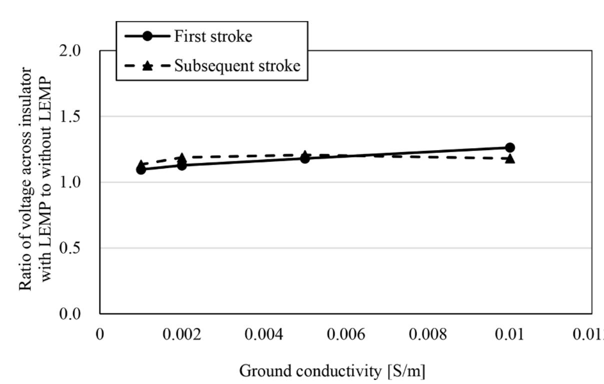


Fig. 10. Ratio between the peak values of the voltages across the insulator calculated by using the LIOV-EMTP model considering LEMP and without considering LEMP, for the case with SAs.

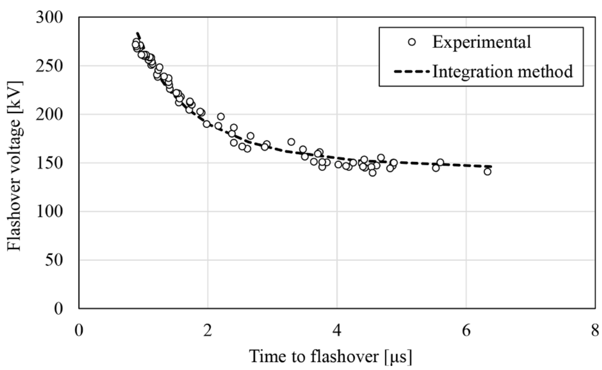


Fig. 11. *V-t* characteristics of 6.6-kV solid core type insulator for positive polarity standard lightning impulse voltage.

4.2. Case A - Line with shield wire only

For the line without SAs, two lightning strike points are considered, as shown in Fig. 12. Table 3 shows the critical multi-phase flashover current values for various ground conductivities, considering the two different lightning current waveforms at the channel base.

The probability of exceeding a certain lightning current peak is calculated by the IEEE distributions, for the first and subsequent stroke waveforms, respectively [29]:

$$P(I) = \frac{1}{1 + (I/31)^{2.6}} \tag{5}$$

$$P(I) = \frac{1}{1 + (I/12)^{2.7}} \tag{6}$$

Assuming an equal number of lightning discharges to the shield wire at top of pole and at the mid-span, the multi-phase flashover probability due to a direct lightning is calculated by averaging the probability of exceeding the critical flashover current shown in Table 3.

Fig. 13 illustrates the influence of the LEMP for different soil conductivity values on the estimated multi-phase flashover probability. The probability of exceeding the critical flashover current significantly increases due to the LEMP effect. With increasing soil conductivity values, the difference between the flashover probabilities with and without the LEMP effect tends to increase, especially for the case of first stroke. This result indicates the importance of LEMP effects in the assessment of the lightning performance of distribution networks when direct strikes are accounted for, even for high ground conductivity soil. In addition, the flashover probability associated with first strokes is larger than that associated to the subsequent stroke waveform.

4.3. Case B - Line with shield wire and SAs

For the line with shield wire and SAs, six lightning strike points are considered as shown in Fig. 14.

Figs. 15 and 16 show the critical multi-phase flashover current and the probability that a lightning event exceeds such a current for the strike points to a pole and in the midspan between two poles. For each current waveform, the probabilities of exceeding the critical flashover current increase as the distance from the SA increases. The larger distance from the pole equipped with SAs, the larger the difference between the probability calculated by considering LEMP contribution and the one obtained without considering LEMP contribution too.

Fig. 17 shows the estimated multi-phase flashover probability for the different soil conductivity values. As for the case without SA, the multi-phase flashover probabilities are obtained by averaging the cumulative probabilities of critical flashover currents at the two direct strike locations, and the flashover probabilities due to a direct lightning have been found to be increased by the LEMP effect. Flashover probabilities associated with subsequent stroke are larger than those associated with first stroke, in agreement to some previous studies for well-protected MV distribution lines [30].

Table 3
Critical multi-phase flashover current and its probability for the case without SA.

(a). First stroke

	Strike points Top of the pole Without LEMP	With LEMP	Mid-span of the shield wire Without LEMP	With LEMP
0.01 S/m	42.5 kA (30.5%)	21.3 kA (72.7%)	70.2 kA (10.7%)	26.6 kA (59.9%)
0.005 S/m	31.9 kA (48.2%)	17.0 kA (82.6%)	47.8 kA (24.5%)	21.3 kA (72.7%)
0.002 S/m	20.2 kA (75.3%)	12.8 kA (91.0%)	26.6 kA (59.9%)	14.9 kA (87.1%)
0.001 S/m	13.8 kA (89.1%)	9.6 kA (95.5%)	17.0 kA (82.6%)	11.2 kA (93.4%)

(b). Subsequent stroke

	Strike points Top of the pole Without LEMP	With LEMP	Mid-span of the shield wire Without LEMP	With LEMP
0.01 S/m	14.5 kA (37.5%)	10.4 kA (59.5%)	21.0 kA (18.1%)	11.5 kA (52.9%)
0.005 S/m	13.1 kA (44.1%)	9.0 kA (68.5%)	20.0 kA (20.1%)	11.5 kA (52.9%)
0.002 S/m	10.5 kA (58.9%)	7.0 kA (81.1%)	15.5 kA (33.4%)	8.0 kA (74.9%)
0.001 S/m	7.5 kA (78.1%)	5.5 kA (89.2%)	11.0 kA (55.8%)	6.5 kA (84.0%)

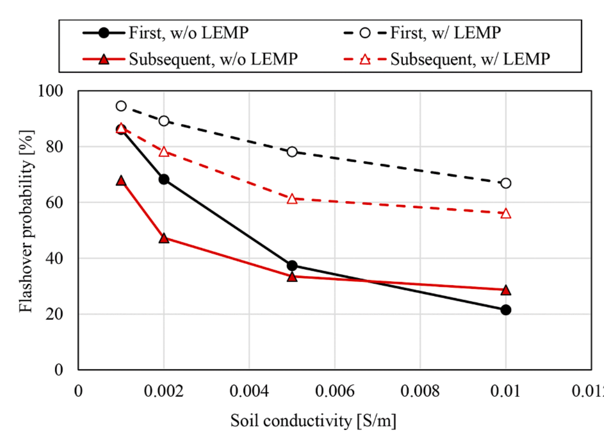


Fig. 13. Estimated multi-phase flashover probability due to a direct lightning for the different soil conductivity – case without SA.

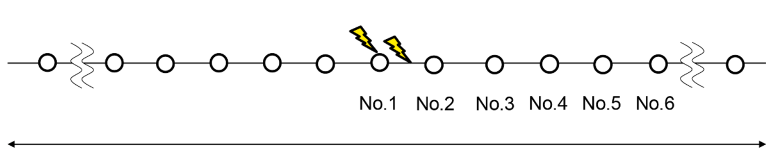


Fig. 12. Considered lightning strike points for the case without SA.

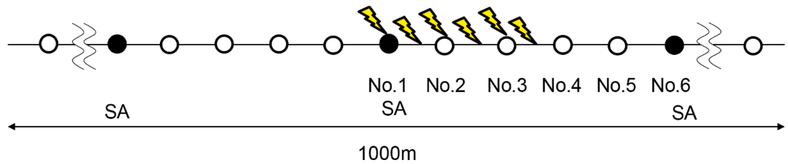


Fig. 14. Considered lightning strike points for the case with SAs located in the posts indicated by black circles.

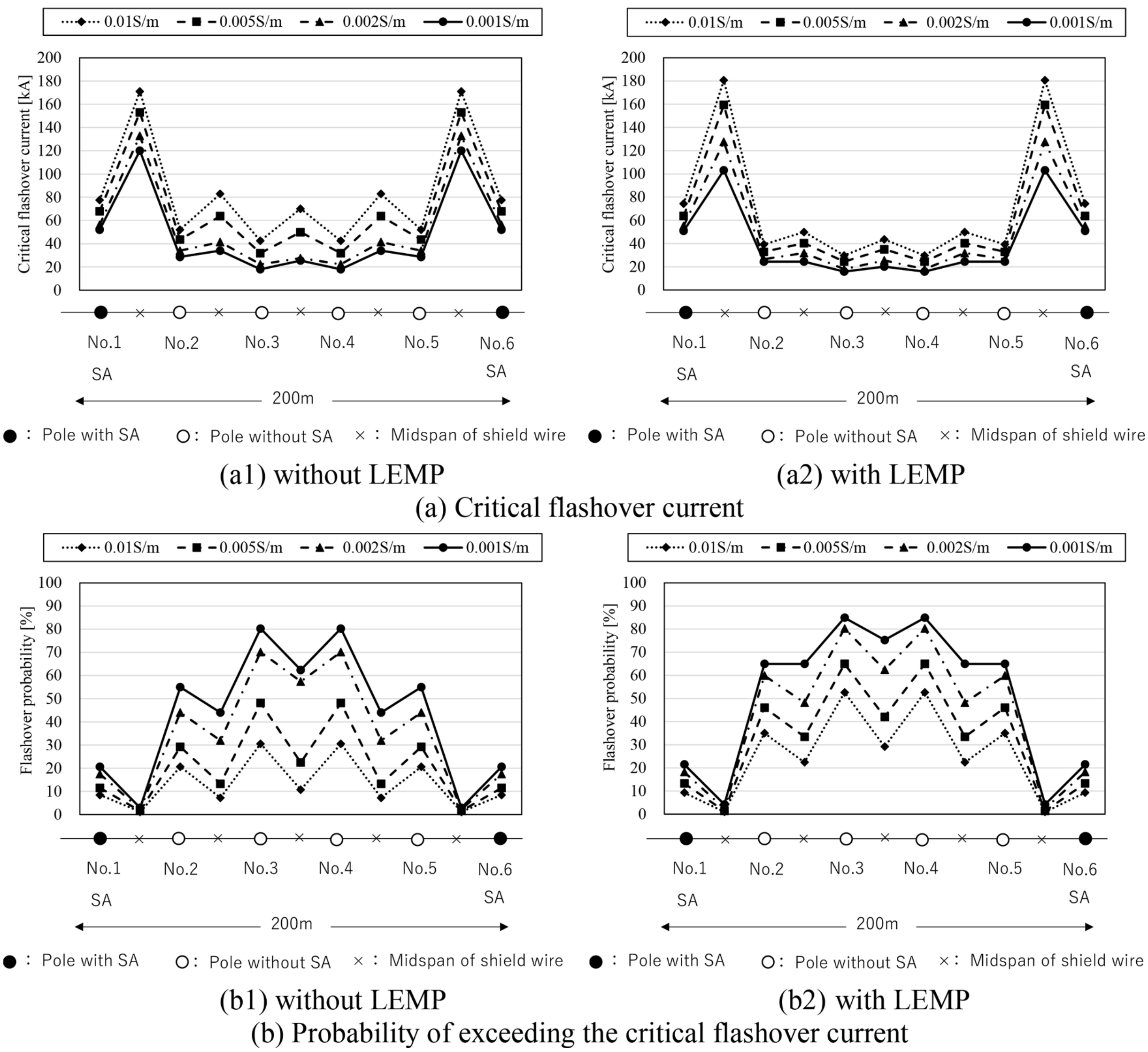


Fig. 15. Critical multi-phase flashover current and its probability for the first stroke in the case with SAs.

In [5], the lightning performance of the considered distribution line was assessed by using a Monte Carlo (MC) method, assuming ground conductivity equal to 0.01 S/m. The MC procedure differs from the one adopted in this paper: the position of the direct events is uniformly distributed over 10 spans and the parameters of the channel-base waveform (peak, front time, maximum front steepness and wavetail time to half value) are generated according to the multivariate distribution described in [31]. Notwithstanding the differences in the calculation procedure, the multi-phase flashover probability due to first strokes predicted in [5] and the one obtained by using the simpler method adopted in this paper are in reasonable agreement. As an example, the multi-phase flashover probability calculated in [5] for the case without SAs is 30% without LEMP and 79.7% considering LEMP, for a ground conductivity of 0.01 S/m. For the case with SAs, the multi-phase flashover probability is 18.7% without considering LEMP and 30.1% by accounting for the LEMP contribution. The differences between the values reported in this paper and those obtained by using the MC method adopted in [5] are lower than 15% for the case without SAs and lower than 10% with SAs, for both the ground conductivity values of 0.01 S/m and 0.001 S/m.

5. Conclusion

This paper extended the previous works by the authors on the same subject by focusing on the influence of the soil conductivity value on the LEMP contribution to overvoltages due to direct lightning strikes. The analysis, carried out by using both the 3-D FDTD method and the LIOV-EMTP code supports the conclusion that the LEMP contribution can have

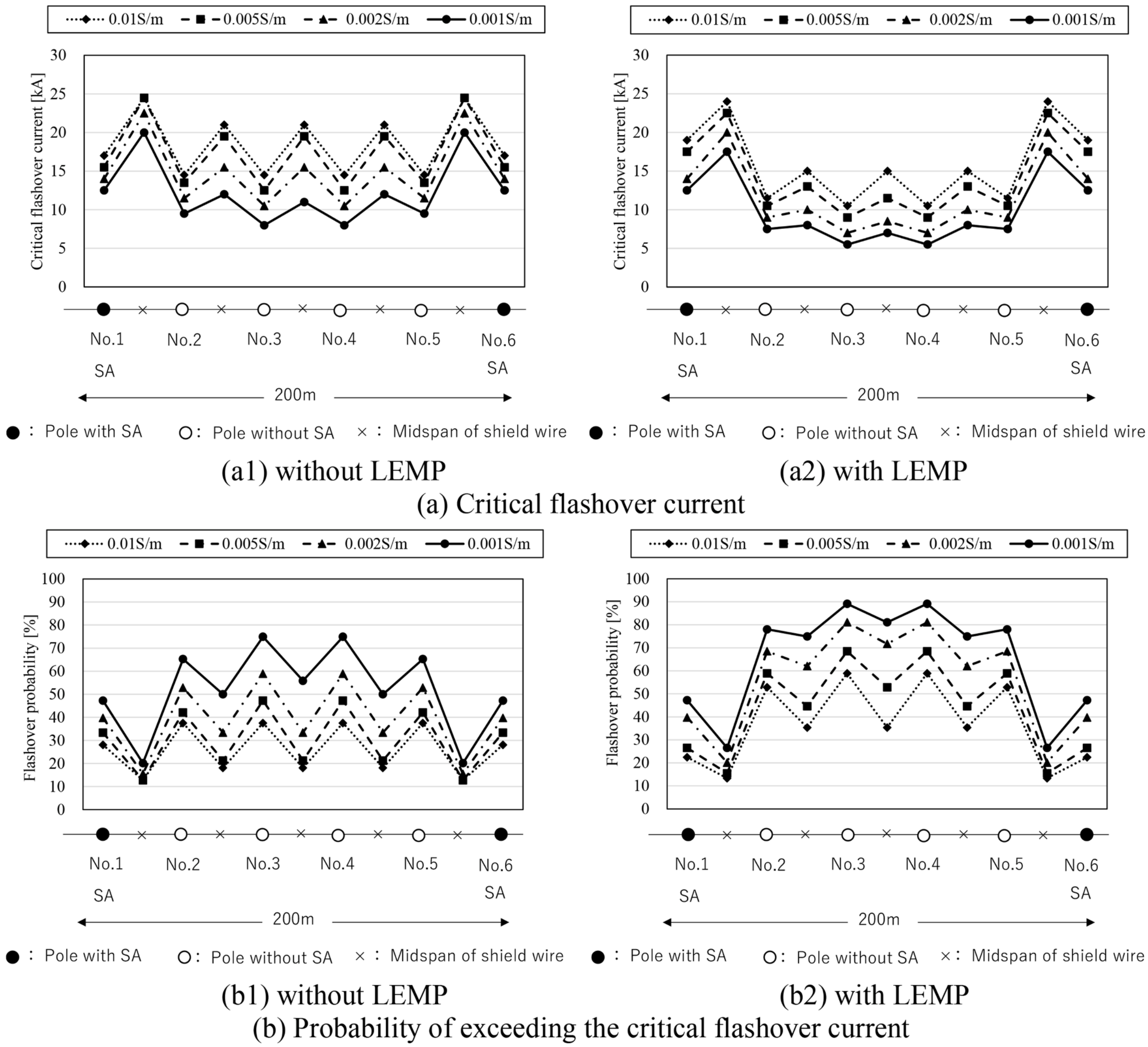


Fig. 16. Critical multi-phase flashover current and its probability for the subsequent stroke in the case with SAs.

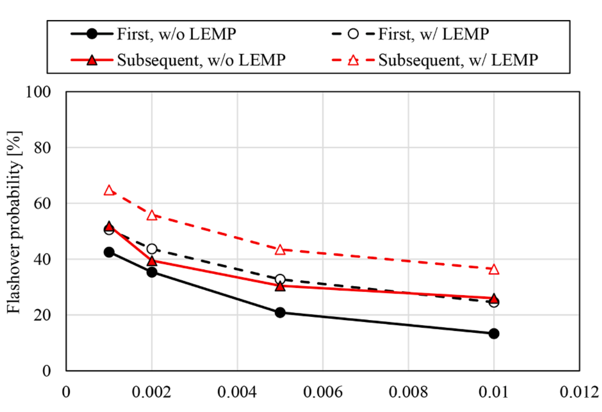


Fig. 17. Estimated flashover probability due to a direct lightning for the different soil conductivity for the case with SA.

an important effect on the direct lightning performance of well-protected overhead distribution lines.

For the assumed grounding system, the voltages across insulators increase as the soil conductivity decreases, which is mainly due to the ground potential rise. On the other hand, the enhancement of the voltage amplitudes considering the LEMP contribution increases with the increase of the soil conductivity, as the ground potential rise is minor for larger conductivity values.

The analysis carried out for well-protected distribution lines, i.e., lines with both shield wire and SAs installed, shows that the flashover probability associated to subsequent strokes may be greater than that due to first strokes.

CRediT authorship contribution statement

Kazuyuki Ishimoto: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Fabio Tossani:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Fabio Napolitano:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Alberto Borghetti:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Carlo Alberto Nucci:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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