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Lightning-Induced Voltage Calculations on an Overhead Insulated Cable

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***Abstract*— In this paper, a study is performed to identify the influence of an insulating layer surrounding an overhead cable on the transient overvoltages induced by nearby lightning strikes. The study is performed considering or neglecting the presence of an insulating layer for different load conditions. It is shown that including an insulating layer might be important to accurately characterize the tail of the resulting transient overvoltages whenever mismatched loads are considered at the line ends. On the other hand, calculated peak voltages are nearly unaffected by the presence of the insulating layer.**

Keywords—Lightning-induced voltages; overhead distribution lines; overhead cables; transient analysis.

I. Introduction

Several techniques are available for calculating lightning-induced voltages on overhead distribution lines. The most popular solution strategy, known as transmission line approach, consists in dividing the problem in three steps [1]. In the first step, the return-stroke channel is represented as an antenna along which the spatial and temporal distribution of the return-stroke current is calculated using a return-stroke model [2, 3]. In the second step, the remote electromagnetic fields generated by the return-stroke current are calculated considering the influence of a lossy ground [4-8]. Finally, in the third step the coupling of the incident electromagnetic fields with the illuminated line is performed using a field-to-line coupling model [9, 10]. The resulting transient is then calculated by solving telegrapher's equations in time domain considering linear or non-linear loads at the line ends [11-16].

The accuracy of the solution obtained with the transmission line approach will depend on the simplifications that are made in each of the steps described above. It will also depend on how accurately the illuminated line is represented, e.g., if ground and conductor losses are included the calculation of the transmission line parameters [17], or if the impulse withstand voltage of the line is correctly accounted for in the flashover rate estimation [18].

In most countries, overhead distribution line configurations are traditionally based on the use of bare cables. However, dielectric-coated cables have been used in Japan for several decades [19, 20]. The use of dielectric-coated cables has also been increasing with the introduction of compact distribution line configurations [21-24]. Nevertheless, lightning-induced voltage calculations on compact distribution lines usually neglect the influence of the insulating layer surrounding the phase conductors [25, 26]. This means that a system of bare cables is ultimately assumed in this type of calculation. The validity of this assumption is yet to be investigated.

In [27], an attempt was made to identify the influence of the insulating layer on the propagation of lightning overvoltages on compact distribution lines. However, the analysis was restricted to the particular case of a direct lightning strike. In this paper, a study is performed to identify the influence of an insulating layer surrounding an overhead cable on transient overvoltages induced by nearby lightning strikes. It is shown that the calculated peak voltages are nearly unaffected by the inclusion of the insulating layer. However, the presence of the insulating layer might be important to accurately characterize the tail of the resulting overvoltages whenever the line is terminated with mismatched loads.

This paper is organized as follows. Section II discusses the modeling assumptions and the simulated cases. Results and analyses are presented in Section III, followed by conclusions in Section IV.

II. Modeling

All simulations considered a 3-km long overhead cable with height of 8.4 m and core radius r extending above a lossy ground with conductivity σ_g and relative permittivity ε_{rg}. The cable is terminated with resistors R_k and R_m, as shown in Fig. 1. A lightning strike is assumed to hit the ground at a point 100 m far from the midpoint of the line, at an equidistant position from the line ends. Induced overvoltages are calculated at the line ends assuming that the overhead conductor is either bare or dielectric-coated, for different load conditions and different insulating layer properties.

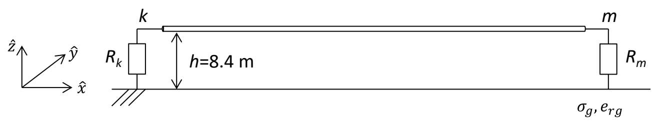

Fig. 1. Overhead cable considered in this study.

The return-stroke current was calculated with the modified transmission line model with exponential decay with height (MTLE model) assuming a straight vertical lightning channel

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[2]. In the simulations, an attenuation constant of $\lambda = 2000$ m and a propagation velocity of 1.5×10^8 m/s were assumed. The channel-base current consists of the sum of two Heidler functions [28] whose parameters are given in [29]. These parameters characterize the median waveform of subsequent stroke currents of negative downward lightning measured at Morro do Cachimbo station, Brazil [29]. The electromagnetic fields generated by the return-stroke current were calculated in the absence of the line using the formulation of Uman and McLain [4], which is valid for a lossless ground. The horizontal electric field component at $h = 8.4$ m was then corrected to account for the influence of a lossy ground using the Cooray-Rubinstein approximation [6, 7]. The coupling of the incident electromagnetic fields with the line was performed with the model of Agrawal, Price and Gurbaxani [10], in which the telegrapher's equations are modified by including terms that depend on the vertical and horizontal components of the incident electric field. For the particular case of a single overhead cable, the resulting equations read

$$\frac{\partial v_s(x,t)}{\partial x} + L_e \frac{\partial i(x,t)}{\partial t} + \varsigma(t) * \frac{\partial i(x,t)}{\partial t} = E_x(x,t), \qquad (1)$$

$$\frac{\partial i(x,t)}{\partial x} + G v_s(x,t) + C \frac{\partial v_s(x,t)}{\partial t} = 0, \qquad (2)$$

where $v_s(x,t)$ is the scattered voltage at coordinate *x* at time *t*, $i(x,t)$ is the induced current, $E_x(x,t)$ is the horizontal component of the incident electric field, calculated at height h in the absence of the line, L_e is the external per-unit-length inductance, $\varsigma(t)$ is the transient impedance, G is the per-unit-length conductance, and C is the per-unit-length capacitance. The total voltage $v(x,t)$ at any point of the line can be calculated as

$$v(x,t) = v_s(x,t) + v_i(x,t), \qquad (3)$$

where $v_i(x,t)$ is approximately given by

$$v_i(x,t) \approx -hE_z(x,t), \qquad (4)$$

where $E_z(x,t)$ is the vertical component of the incident electric field calculated at the ground surface right below the line.

The transient impedance $\varsigma(t)$ in (1) is defined as

$$\varsigma(t) = \mathcal{L}^{-1}\left\{\frac{Z_i + Z_g}{s}\right\}, \qquad (5)$$

where Z_i is the internal impedance of a solid cylindrical conductor, calculated with the approximate expression given in [30], Z_g is the ground-return impedance, obtained with Sunde's formula [31], s is the Laplace variable and the operator $\mathcal{L}^{-1}\{\cdot\}$ indicates the inverse Laplace transform of its argument. In this paper, $(Z_i + Z_g)/s$ is fitted as a sum of rational functions using the vector fitting technique. As a consequence, $\varsigma(t)$ is approximated as a sum of exponential functions. Assuming a cable with DC resistance of 0.822 Ω/km and $r = 4.1$ mm positioned above a lossy ground with $\sigma_g = 0.002$ S/m and $\varepsilon_{rg} = 10$, 20 exponential terms were used for representing $\varsigma(t)$.

The solution of (1) and (2) is performed directly in the time domain using a 1st order finite-difference time-domain (FDTD) scheme [32]. The convolution integral between $\varsigma(t)$ and $\partial i(x,t)/\partial t$ in (1), written in compact form as '*', is solved recursively as indicated in [32]. All simulations considered $G = 0$.

For calculating the per-unit-length capacitance, the overhead cable was considered either bare or covered by a dielectric layer with different values of thickness δ and permittivity ε_r. A formulation based on the method of moments (MoM), described in [33, 34], was considered for accurately determining this parameter. Since the insulating layer does not have magnetic properties, the per-unit-length inductance L_e was calculated using the expression valid for a bare cable when $h \gg r$ [32].

III. Results and Analysis

A. Matched line

In this section, lightning-induced voltages are calculated assuming that the line is terminated with 500-Ω resistors. Since this value approaches the characteristic impedance of the line, the line can be considered effectively matched. Three different cases were simulated as shown in Table I. Case 1 corresponds to a bare cable. Case 2 considers typical values of δ and ε_r used in compact distribution lines [22]. Case 3 is a hypothetical condition selected to illustrate the effect of increased values of insulation thickness and relative permittivity on the resulting overvoltages.

TABLE I. Simulation parameters

	r (mm)	δ (mm)	ε_r
Case 1	4.1	-	-
Case 2	4.1	3.05	2.3
Case 3	4.1	6.10	10

The voltages calculated at the sending end of the line, shown in Fig. 2, indicate that the inclusion of the insulating layer does not to have a significant effect on the calculated voltages. In fact, the results obtained for cases 1 and 2 are nearly equivalent. Only for case 3, which considers increased values for δ and ε_r, small deviations are observed in the calculated voltage waveform with respect to the waveform obtained for a bare cable. Even so, such deviations are negligible both in the initial negative peak and in the subsequent positive peak observed in the figure.

B. Open-ended line

The simulations are now repeated considering an open-ended line. The voltages calculated at the sending end of the line are shown in Fig. 3. Similarly as observed for the matched line case, if both ends of the line are left open the initial negative voltage peak is nearly unaffected by the consideration of the cable insulation. The same comment applies to the first positive peak occurring at about 8.5 μs. As time elapses, however, successive reflections take place at the line ends. Although the peak values of the oscillatory waveforms are nearly the same, differences are observed in their time of occurrence. The voltage waveform associated with the bare cable, referred to as case 1, is the one that has the shortest period of oscillation. This is related to the fact that the wave velocity associated with a bare cable approaches the speed of light as frequency increases. As a consequence, the waves reflected at the line terminations require less time to travel from one end to the other. For cases 2 and 3, however, the wave velocity approaches a limiting value that is lower than the speed of light due to the presence of the insulating layer [27]. Consequently, the period of oscillation increases with increasing the thickness and the relative permittivity of the insulation. The most remarkable time delay observed at the wave tail refers to case 3, but the values of δ and ε_r corresponding to this case cannot be considered entirely realistic. For the more practical condition expressed in case 2, the calculated waveform does not vary much compared to the bare cable case.

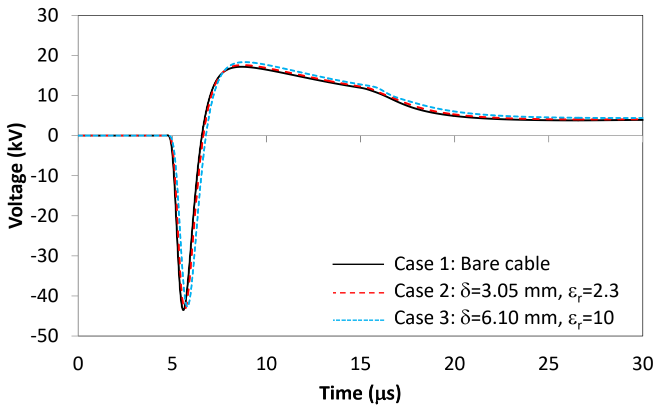

Fig. 2. Voltages at terminal k of the line for $R_k = R_m = 500\ \Omega$.

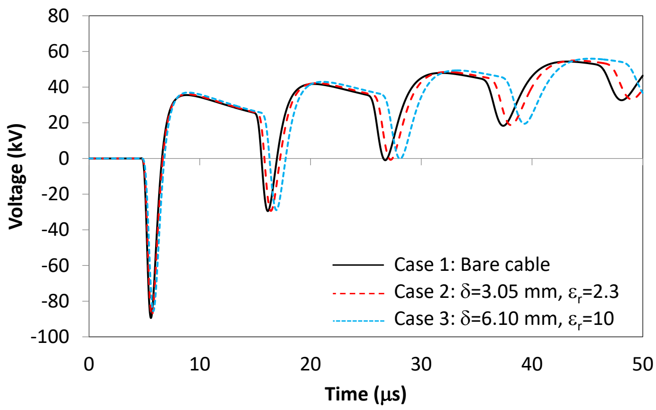

Fig. 3. Voltages at terminal k of the line for $R_k = R_m = \infty$.

C. Assymetrical line termination

The last condition investigated in this paper assumes that the sending end of the line is connected to a 10-Ω resistor, while the receiving end of the line is left open. This hypothetical case could represent, for example, the case where one of the line ends is short-circuited to ground due to a flashover while the other end is naturally open. The conditions indicated in Table I are once again considered. Voltages calculated at the sending end of the line are shown in Fig. 4. Voltages at the receiving end are illustrated in Fig. 5.

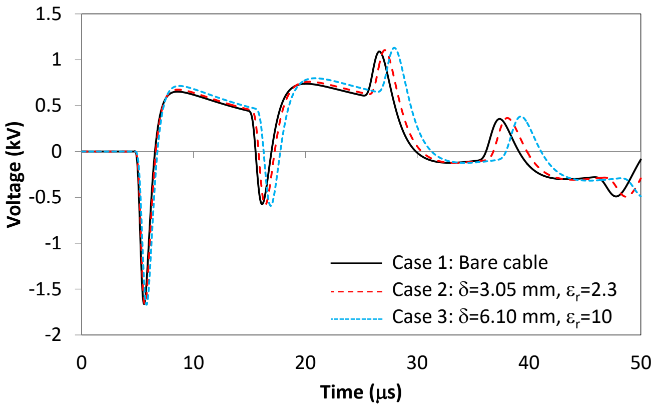

Fig. 4. Voltages at terminal k of the line for $R_k = 10\ \Omega$ and $R_m = \infty$.

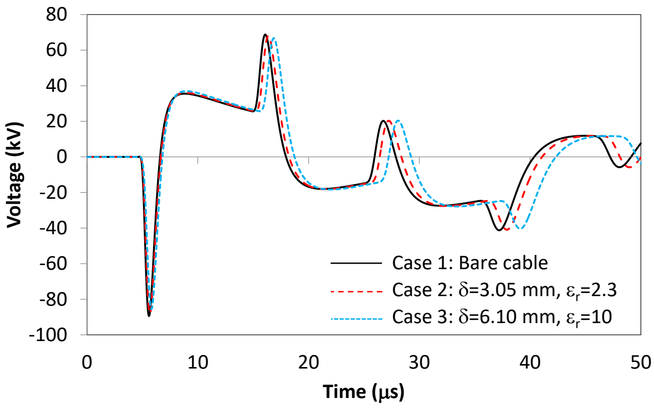

Fig. 5. Voltages at terminal m of the line for $\mathrm{R_k} = 10\ \Omega$ and $\mathrm{R_m} = \infty$.

The same conclusions drawn from studying the open-ended line in the previous section hold for the particular case considered in this section. This happens because the calculated voltage waveforms once again exhibit an oscillatory nature due to the impedance mismatch at the line ends. As before, the calculated peak values are not significantly affected by the inclusion of the insulating layer, only their time of occurrence.

IV. Conclusions

This paper studied the influence of an insulating layer on lightning-induced voltages on a single overhead cable. This study was motivated by the increasing use of dielectric-coated phase cables in distribution lines and by the fact the presence of the insulating layer is frequently neglected in this type of study.

For the case of a single overhead cable it is shown that the presence of an insulating layer is not likely to significantly affect the peak values of the induced voltages, especially if the line is matched at both ends. If the line is unmatched, successive reflections take place at the line ends. These voltage reflections present a period of oscillation that is affected by the presence of the insulating layer. It was observed that the period of oscillation increases with increasing the thickness and the relative permittivity of the insulation. This leads to an increase in the time of occurrence of successive peaks. However, the overall characteristics of the resulting waveforms remain unchanged. In fact, for practical values of insulation thickness and relative permittivity, the calculated voltage waveforms are nearly identical to those obtained for a bare cable, especially at early times. This indicates that, for the tested conditions, lightning-induced voltage calculations could be performed assuming a bare cable without significant loss of accuracy.

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