INFLUENCE OF CORONA ON LIGHTNING-INDUCED VOLTAGES ON OVERHEAD POWER LINES

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Abstract - A model for the calculation of lightning-induced voltages is presented allowing the assessment of the effect of corona when power distribution lines are illuminated by lightning electromagnetic fields. It is shown that, as far as corona can be described by means of an increase of capacitance after the voltage has reached a threshold value, corona can produce an increase in the peak amplitude of the induced voltage. An explanation of this result is given. The need for experimental results to test this theoretical finding is stressed in the paper. It is also shown that for lightning-induced voltage calculations, the ground resistivity plays a more important role than the corona in modifying the wave shape of the induced surges. This is different from the direct-strike behaviour, and is due to the fact that the ground resistivity affects more strongly the lightning-radiated fields rather than the surge attenuation along the line, while corona affects only surge propagation.

1. INTRODUCTION

Theoretical and experimental studies show that corona is the main cause of attenuation and distortion of the travelling waves for the case of *direct* strikes to HV transmission lines [1-4]. However, for the case of voltages induced by *nearby* lightning on distribution lines (lightning-induced voltages), the finite value of the ground conductivity is generally considered to be the most important factor determining the wave-shape change of the induced voltages [5,6].

In some instances, some of the calculated and measured voltages induced on distribution lines can reach magnitude above the corona threshold, especially in the case of particularly severe excitation conditions, e.g. stroke locations very close to the line or high values of the return-stroke current amplitude.

The aim of the paper is to investigate whether corona effect should be considered when calculating lightning-induced voltages and, in this case, how it would affect the induced voltage wave shape and magnitude. Indeed, the accurate evaluation of intensity and wave shape of the induced surges is of importance for the appropriate design and co-ordination of protection and insulation.

To accomplish this, in Section 2 the 'coupling' model by Agrawal et al. [7], describing the interaction between an external field and a transmission line, will be extended to take into account the influence of corona on the induced voltages. Then, in Section 3, the results of some computations aimed at discussing the effect of corona on the induced overvoltages will be presented. Differences and analogies between our results and others which refer to the case of direct strikes, will be discussed. Section 4 will be devoted to the conclusions.

2. MODELLING OF LIGHTNING-INDUCED VOLTAGES IN PRESENCE OF CORONA

2.1. Coupling model. The voltage induced on an overhead line above a lossy ground by an indirect return-stroke can be calculated by means of the model by Agrawal et al. (henceforth called the Agrawal model), which is described by the two following coupling equations [7,6]

$$\frac{\partial u^s(x,t)}{\partial x}+\int_0^t z_g^{'}(\tau)\cdot i(x,t-\tau)d\tau+L'\,\frac{\partial i(x,t)}{\partial t}=E_x^i(x,h,t) \qquad (1)$$

$$\frac{\partial i(x,t)}{\partial x}+C' \;+G'u^s(x,t)\frac{\partial u^s(x,t)}{\partial t}=0 \qquad (2)$$

where

- $E_x^i(x,h,t)$ is the horizontal component of the incident electric field along the x axis at the conductor's height;
- $i(x,t)$ is the current induced along the line;
- $z_g^{'}(t)$ is the inverse Fourier-transform of the per-unit-length (p.u.l.) ground impedance [8], here assumed to be much greater than the wire impedance [6];
- L' and C', G' are the p.u.l line inductance, capacitance and conductance respectively.

Equations (1) and (2) are written in terms of *scattered* voltage $u^s(x,t)$. The total voltage $u(x,t)$ is given by the sum of the scattered voltage $u^s(x,t)$ and the so-called *incident* voltage

$$u^i=-\int_0^h E_z^i(x,z,t)dz\approx -E_z^i(x,0,t)\cdot h \qquad (3)$$

namely,

$$u(x,t)=u^s(x,t)+u^i(x,t) \qquad (4)$$

The boundary conditions are

$$u^s(0,t)=-R_0\,i(0,t)-u^i(0,t) \qquad (5)$$

$$u^s(L,t)=R_L\,i(L,t)-u^i(L,t) \qquad (6)$$

The incident field appearing in (1)-(6) is calculated by using the Modified Transmission Line (MTL) return-stroke model [9], which by using reasonable approximations, is able to predict fields from both natural and triggered lightning[1]. Such a field is given by the sum of the field radiated by the lightning channel and the ground reflected field, both considered in absence of the wire.

Note that in the determination of lightning-induced voltages, the ground resistivity appears at two points: I) in the calculation of the incident field and II) in the calculation of the line parameters (ground impedance).

For the calculation of the incident field (point I), we use the approach recently proposed by Rubinstein [11,12] which is a good compromise between accuracy and computation time [6] (an equivalent approach has been independently proposed by Cooray [13,14]).

For the calculation of the ground impedance (point II), we will assume it is independent of the frequency, and calculate it at the fixed frequency of 100 kHz. Such an assumption, adopted by other authors when studying corona for the case of direct strike to the line [15], appears reasonable also in view of the results recently obtained in [6] [2].

2.2. Corona model. From a macroscopic point of view, corona can be described by a charge-voltage curve [2]. After an initial linear increase of the charge with the voltage, a threshold voltage ($u_{th}(x,t)$) is reached and a sudden change of the derivative of charge with respect to the voltage takes place. This derivative defines a voltage-dependent dynamic capacitance (C_{dyn}). We here consider a simplified corona model given by [3]

$$\begin{aligned}
&C_{dyn}(x,t)=C_0 \qquad (\text{for } u(x,t)<u_{th}(x,t))\\
&C_{dyn}(x,t)=C_0(k_1+k_2(u(x,t)-u_{th}(x,t))/u_{th}(x,t))\\
&\qquad\qquad (\text{for } u(x,t)>u_{th}(x,t) \text{ and } \frac{\partial u(x,t)}{\partial t}>0)\\
&C_{dyn}(x,t)=C_0 \qquad (\text{for } \frac{\partial u}{\partial t}<0) \qquad\qquad (7)
\end{aligned}$$

where

k_1 (≥1) is related to the sudden change of the capacitance when the voltage exceeds the corona threshold u_{th}(typical values are in the range 1.5-3), and

k_2 (≥0) is related to the gradual increase of the capacitance when the voltage is rising above the threshold.

A value of $k_2 = 0$ corresponds to the simplest approach to model corona.

The threshold voltage is initially determined by means of the Peek's formula (e.g. [16]), considering a surface irregularity coefficient of 0.65. Then it is updated by taking the maximum value the voltage has reached during the time corona is active, in order to allow for the treatment of multi-pulse overvoltages [17].

No variation in the inductance has been considered, since the conductivity of the corona sheath around the conductor is small compared to that of the wire. This assumption implies that the current flows primarily in the wire [18].

2.3. Equivalent coupling circuit. The equivalent coupling circuit describing the interaction between an incident electromagnetic field and a single-conductor overhead line, according to the Agrawal model, is shown in Fig. 1. The dynamic capacitance which is aimed at describing corona, is shown in the figure. Also, the resistance p.u.l. of the line is reproduced, which, as already mentioned, is assumed not to vary with frequency.

According to the Agrawal model, lightning-induced voltages are the result of various sources contributions: the sources along the line (proportional to the horizontal electric field), and two sources proportional to the vertical electric field at the two vertical line terminations, the so-called 'risers' (see Fig. 1).

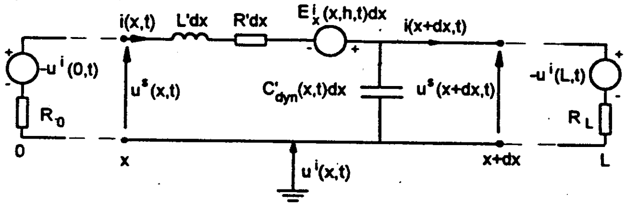

Fig. 1. Differential equivalent coupling circuit according to the Agrawal et al. formulation for a single-wire overhead line in which the capacitance p.u.l has been modified to account for corona effect.

3. NUMERICAL SIMULATIONS AND DISCUSSION

The corona equations (7) have been implemented into a code for the calculation of lightning-induced voltages (LIOV [19]) based on the finite-difference point-centered method.

We now apply the code to calculate the overvoltages induced on a 2 km long, 7.5 m high, single-conductor overhead line, by a return stroke with a

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[1] Other return-stroke models however, (see [10] for a survey), could be adopted without modifying the basic conclusions of this paper.

[2] Indeed, in [6] induced voltages are calculated for a 1 km long line and for ground conductivities of 0.001 S/m, taking into account the effect of the ground conductivity in both field calculation using the Rubinstein-Cooray approach (point I), and in the calculation of the ground impedance by applying the convolution theorem (point II). In [6] it is shown that, for lines not longer than 2-3 km, the effect of the ground resistivity on point I, is much more important than on point II. This means that for the calculation of the ground impedance, at least for similar cases to that studied in [6], a simplified method for the evaluation of such a paremeter is justified.

current peak-value $I_p = 50$ kA and a maximum front-steepness $(di/dt)_{max} = 40$ kA/µs. We choose two stroke locations: stroke location A and stroke location B, as shown in Fig. 2. For the assumed stroke locations higher peak values of the lightning current are expected to result in direct strikes to the line [20].

We will first consider the ground as a perfectly conducting plane, and then we will repeat the calculation assuming a finite ground conductivity.

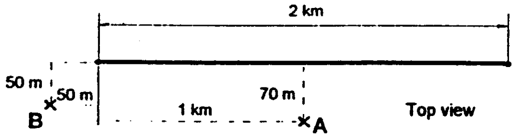

Fig. 2. Geometry of the case-study line.

The overvoltages induced at the termination of the line (matched) for the case of stroke location A are shown in Fig. 3 in solid line. In Fig. 3a corona effect has been disregarded, whereas in Fig. 3b it has been taken into account. For illustrative purposes, the contributions to the total overvoltage of the incident voltage, of the voltage due to the horizontal electric field and of the voltage due to the vertical electric field coupling with the risers, are shown. It can be seen that, for the case of lightning-induced overvoltages, corona produces the well-known increase of the rise time (of the order of 2.5 µs in Fig. 3b, instead of about 1.5 µs of Fig. 3a. However, it also produces an increase in the peak value (of about 135 kV instead of 100 kV), contrary to the peak reduction observed for direct strikes to the line.

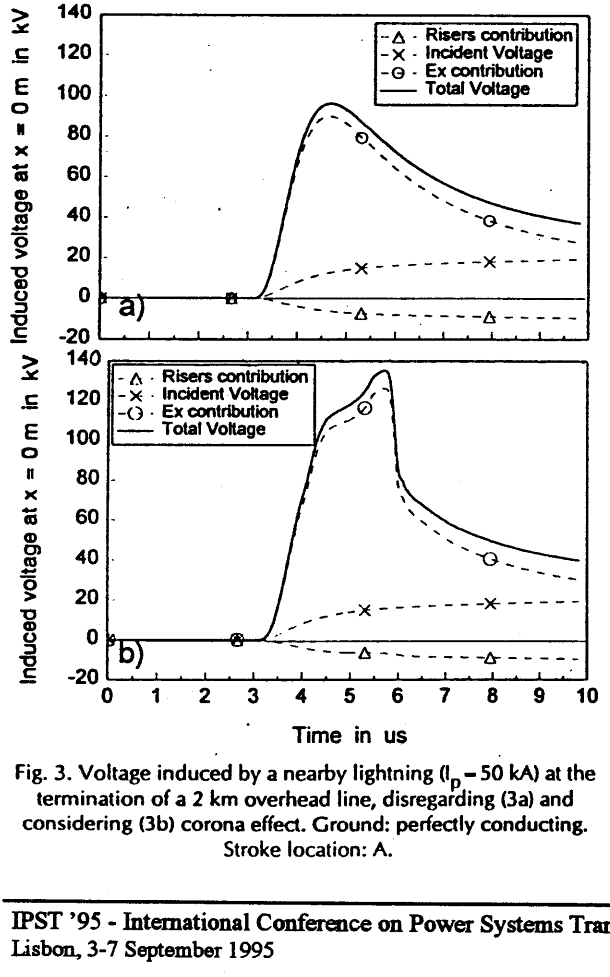

Fig. 3. Voltage induced by a nearby lightning ($I_p = 50$ kA) at the termination of a 2 km overhead line, disregarding (3a) and considering (3b) corona effect. Ground: perfectly conducting. Stroke location: A.

Within the limits of the simple model we have adopted in this paper, this result can be explained as follows. As shown in Fig. 3, for an observation point at the line termination and for a stroke location equidistant to the terminations, the induced voltage is practically given by only the contribution of the horizontal-field sources along the line [3]. Fig. 4 illustrates schematically the mechanism of formation of the induced voltage for this case, in which the horizontal field contribution is dominant. Now, if the line-capacitance increases at some points along the line, as assumed by the corona model, the wave propagation velocity decreases. This means that, as shown in Fig. 4c, all of the propagation times τ_i of the contribution of each of the various voltage sources along the line increase. Therefore, the resulting total voltage would reach a higher peak, given by the sum of the two contributions $\Delta x \cdot E_{x1}/2$ and $\Delta x \cdot E_{x2}/2$, since the subtractive contribution $\Delta x \cdot E_{x3}/2$ will start to produce its action later.

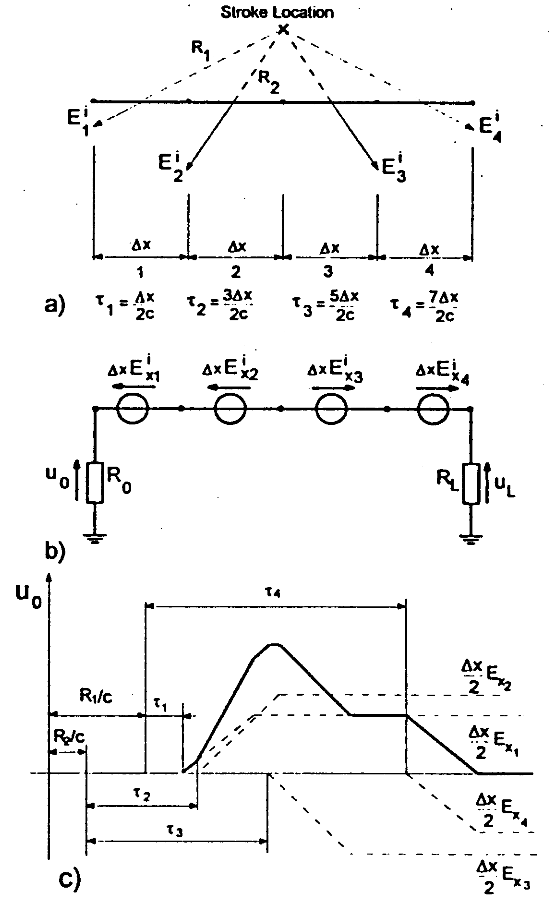

Fig. 4. Schematic explanation of the wave shape of the induced voltage due to the horizontal field according to the Agrawal model. (Adapted from [22,23])

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[3] The above statement results from the adoption of the Agrawal model. According to other equivalent but different coupling models other components of the electromagnetic field would appear to 'dominate' the coupling mechanism [21]. This issue, which is beyond the scope of this paper and which is thoroughly discussed in [21] , does not modify the basic conclusions reported here .

Similar, but more complex reasoning can be made for different stroke locations and for different observation points. However, as we will see below, this does not modify the basic conclusion reported above.

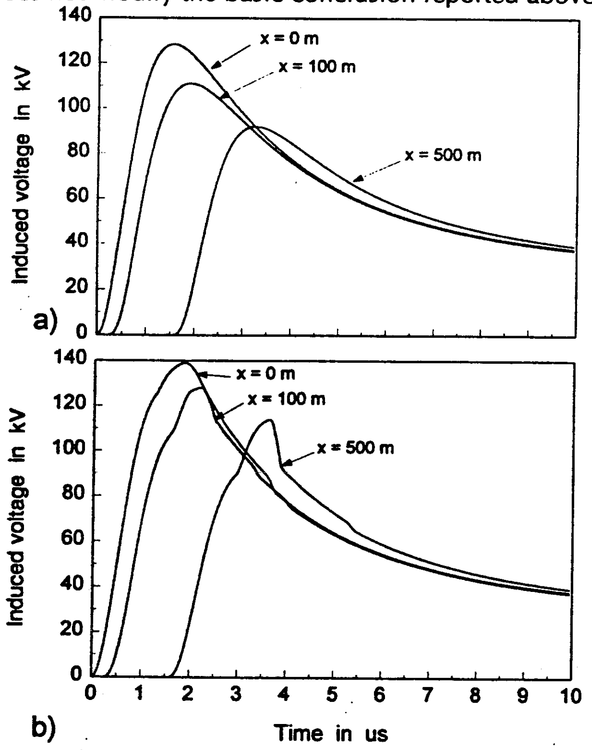

Fig. 5. Voltage induced by a nearby lightning (I_p = 50 kA) calculated at three position along the overhead line, disregarding (5a) or considering (5b) corona effect. Ground: perfectly conducting. Stroke location: B.

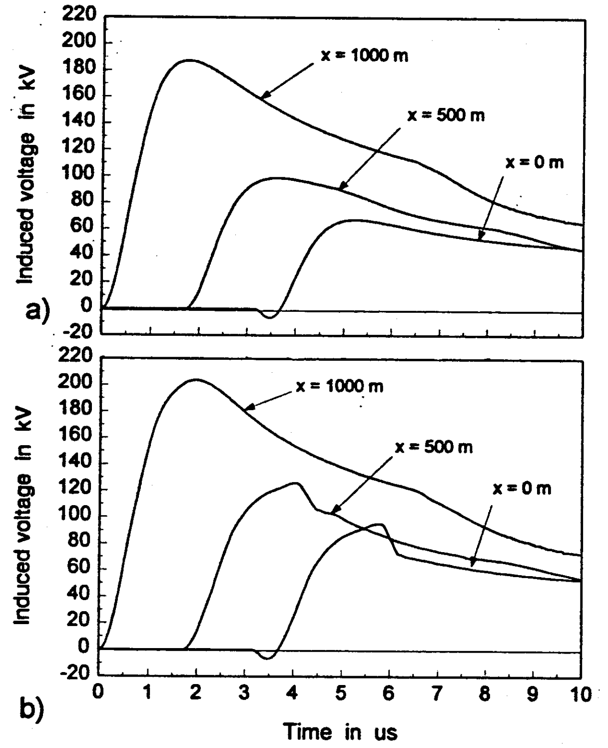

Fig. 6. Voltage induced by a nearby lightning (I_p = 50 kA) calculated at three position along the overhead line, disregarding (6a) or considering (6b) corona effect. Ground conductivity: σ_g = 0.01 S/m, ε_{rg} = 10. Stroke location: A.

In Fig. 5 similar calculations to those relevant to Fig. 3, but for stroke location B, are reported. (The termination closer to the stroke location is now open-circuited). Again, the increase in the peak amplitude of the induced voltage can be observed.

We now repeat the calculations of Figs. 3 and 5, considering a finitely conducting ground with a conductivity $\sigma_g = 0.01$ S/m and a relative permittivity $\varepsilon_{rg} = 10$, adopting the models mentioned in Sect. 2. The results are shown in Figs. 6 and 7.

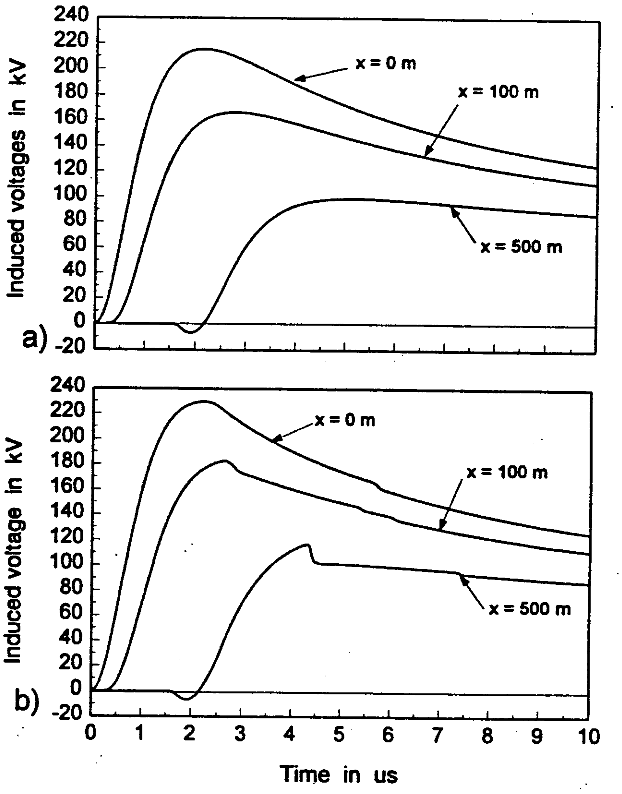

Fig. 7. Voltage induced by a nearby lightning (I_p = 50 kA) calculated at three position along the overhead line, disregarding (7a) or considering (7b) corona effect. Ground conductivity: σ_g = 0.01 S/m, ε_{rg} = 10. Stroke location: B.

From Figs. 6 and 7 one can infer that, while for the case of direct strikes to HV lines there is evidence that the distortion of the surges is due essentially to corona and that the finite ground conductivity is not an important factor [15], for the case of lightning-induced voltages, both effects (of ground conductivity and of corona) are to be taken into account to evaluate the surge distortion.

However, it is important to state that only for peak values of the lightning current of the order of 50 kA we were able to observe corona in our simulated induced voltages. For lower values of the return-stroke current and/or for more distant stroke locations, corona seems not to be a problem of interest for distribution lines illuminated by lightning electromagnetic fields.

4. CONCLUSIONS

This theoretical study gives some hints that it might be necessary to take corona effects into account when calculating lightning-induced voltages on distribution lines, although only for particularly severe conditions, namely for very close stroke locations (some tens meters) and for high peak values of the lightning current (around 50 kA for a distance of 50 m from the line).

In particular, the simple corona model used in this paper predicts an increase in the rise-time of the induced surges, as for the case of direct strikes. However, contrary to the peak reduction observed for direct strikes, corona acts to increase the magnitude of the lightning-induced voltages. This result has been discussed and, within the limits of the model adopted to describe corona, also justified. Experimental results aimed at testing the theoretical findings of this paper are needed.

While, for the case of direct strikes to HV lines, there is evidence that the distortion of the surges is due essentially to corona and that the finite ground conductivity is not an important factor, for the case of lightning-induced overvoltages both effects (of ground conductivity and of corona) are, in principle, to be taken into account.

This result is due to the fact that the ground resistivity affects more strongly the radiated electromagnetic fields (and therefore the coupling between the field and the transmission line) rather than the surges attenuation along the line.

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