Corona on Multiconductor Overhead Lines Illuminated by LEMP

M. T. Correia de Barros, J. Festas
IST - Universidade Técnica de Lisboa /
Instituto da Energia – INTERG,
1096 Lisboa Codex, Portugal.

C. A. Nucci
University of Bologna,
Department of Electrical Engineering,
40136 Bologna, Italy.

F. Rachidi
Swiss Federal Institute of Technology,
Power Systems Laboratory,
1015 Lausanne, Switzerland.

Abstract – **Two corona models, applicable to the calculation of lightning-induced overvoltages in multiconductor overhead lines, are considered in this paper. The first model represents corona by an increase in each conductor self capacitance after the voltage has reached a threshold value, and in the second model, the influence of corona on the mutual coupling between conductors is also taken into account. Results show that corona (using any of the models) produces an increase in the overvoltage amplitudes, confirming what found in a previous work concerning single-conductor lines. It can also be seen that the results obtained by each model are quite different from each-other. The effect of corona in mutual coupling should not be disregarded.**

Keywords: Induced Overvoltages, Multiconductor Lines, Corona.

I. INTRODUCTION

Usually, in the calculation of lightning-induced overvoltages, corona is not taken into account because it is generally agreed that the overvoltage amplitudes are not high enough to produce this effect. However, for the case of stroke locations very close to the line or for high values of the return-stroke current amplitude, the overvoltage amplitudes can reach the threshold voltage.

Previous work [1] has shown that, for the case of single conductor lines, corona produces an increase in the amplitudes of the lightning-induced overvoltages. Theoretical explanation of this result has also been provided in [1].

In this paper, in order to investigate the corona effect on the overvoltages induced on a multiconductor overhead power line, two corona models are used: in the first model corona is represented by an increase of each conductor self capacitance after the voltage has reached a threshold value; in the second model, the influence of corona in the mutual coupling between conductors is also taken into account.

The line model uses the coupling model proposed by Agrawal et al. [2] and the numerical solution is the one described in [3]. Both these models were tested with good results in [4].

The "LEMP" program developed in [5] is used to calculate the vertical and horizontal electric fields produced by the lightning return-stroke, which illuminate the line.

The results obtained with and without corona, as well as the ones obtained with both corona models, are presented and discussed.

II. COUPLING MODEL

Agrawal et al. [2] derived the equations describing the coupling of an external electromagnetic field and a multiconductor line in the time domain. Starting from Maxwell's equations and considering transverse magnetic propagation, the following pair of expressions are proposed for the case of a lossless line,

$$\frac{\partial}{\partial x}\left[u_i^s(x)\right]+\left[L'_{ij}\right]\frac{\partial}{\partial t}\left[i_i(x)\right]=\left[E_x^i(x,h_i)\right] \qquad (1)$$

$$\frac{\partial}{\partial x}\left[i_i(x)\right]+\left[C'_{ij}\right]\frac{\partial}{\partial t}\left[u_i^s(x)\right]=0 \qquad (2)$$

where:

- $\left[L'_{ij}\right]$ is the inductance matrix per unit length of the line;
- $\left[C'_{ij}\right]$ is the capacitance matrix per unit length of the line;
- $\left[E_x^i(x,h_i)\right]$ is the vector of the horizontal component of the incident electric field at conductor *i* height, h_i;
- $\left[i_i(x)\right]$ is the vector of the line currents, and
- $\left[u_i^s(x)\right]$ is the vector of the scattered voltages.

To obtain the total voltage, it is necessary to add to the scattered voltage the voltage of the incident field between the reference and the *i*th conductor,

$$\begin{aligned}\left[u_i(x)\right]&=\left[u_i^s(x)\right]-\left[\int_0^{h_i}E_z^i(x,z)dz\right]\\&\cong\left[u_i^s(x)\right]-\left[h_iE_z^i(x,0)\right]\end{aligned} \qquad (3)$$

where:

- $\left[E_z^i(x,0)\right]$ is the vertical component of the incident electric field, considered unvarying in the height range $0<z<h_i$.

In (1)-(3), the time dependency of voltage, current and electric field vectors is omitted for sake of simplicity.

Finally, we report the two expressions (one for each line terminal) representing the boundary conditions in terms of scattered voltage:

$$\left\lfloor u_i^s(x=0)\right\rfloor = -[R_0][i_i(x=0)] + \left\lfloor h_i E_z^i(x=0, z=0)\right\rfloor \quad (4)$$

$$\left\lfloor u_i^s(x=L)\right\rfloor = [R_L][i_i(x=L)] + \left\lfloor h_i E_z^i(x=L, z=0)\right\rfloor \quad (5)$$

where $[R_0]$ and $[R_L]$ are the matrices of the line terminations.

III. CORONA MODEL

A. Simplified 'single-phase' model

In the case of multiconductor lines, the usual approach to corona is to consider each conductor separately from the others. In this case, and from a macroscopic point of view, corona can be described by a charge-voltage curve [6], where a sudden change of the derivative of charge with respect to the voltage takes place after a threshold voltage is reached ($u_{thi}(x,t)$) on a conductor. This derivative defines a voltage-dependent dynamic self capacitance for conductor i ($C_{dynii}(x,t)$). The considered simplified corona model, corresponds to the simplest approach proposed in [7] and is given by:

$$C_{dynii} = C_{0ii} \qquad (\text{for } u_i(x,t) < u_{thi}(x,t))$$

$$C_{dynii} = \gamma_i . C_{0ii} \qquad \left(\text{for } u_i(x,t) > u_{thi}(x,t) \text{ and } \frac{\partial u_i(x,t)}{\partial t} > 0\right)$$

$$C_{dynii} = C_{0ii} \qquad \left(\text{for } \frac{\partial u_i(x,t)}{\partial t} < 0\right) \qquad (6)$$

where γ_i is related to the sudden change of the self capacitance when the conductor voltage exceeds the corona threshold u_{thi} (typical values are in the range 1.5-3).

The threshold voltage is determined using Peek's formula:

$$u_{thi} = \frac{2\pi\varepsilon_0 r_i}{C_{0ii}} e_{thi} \qquad (7)$$

where

$$e_{thi} = m_{si} . 31\left(1 + \frac{0.308}{\sqrt{r_i}}\right), \qquad (8)$$

is the threshold electric field, r_i is the conductor i radius and m_{si} is a surface irregularity coefficient (considered 0.8 in this study).

B. Multi-phase model

A second corona model, originally proposed in [8], is also used. This model takes into account the corona effect on the mutual coupling between the conductors and can be described by the following equation:

$$C_{dynij} = C_{0ij} + \sum_k \frac{C_{0ik} C_{0kj}}{C_{0kk}} (\gamma_k - 1) \qquad (9)$$

Equation (9) can be applied when corona is either active or not, on each conductor k, considering $\gamma_k = 1$ when corona is not active.

It should be noted that in this model, γ_k is controlled by the field at conductor k and not by the voltage u_k. When the electric field at conductor k surface reaches the threshold value given by (8) corona starts at that conductor.

This model is more complete, and expected to reproduce more accurate results.

IV. RESULTS USING THE 'SIMPLIFIED' SINGLE-PHASE CORONA MODEL

In our analysis we will consider two lines (Fig. 1.a and Fig. 1.b) previously used in other studies [4,9,10], one having vertical configuration and the other horizontal configuration. The radius of the conductors on each line is 9.14 mm and both lines are 1 km long. As in [9], all the conductors are terminated on a resistance equal to its characteristic impedance determined in the absence of other conductors.

In order to calculate the electric fields illuminating the lines we used the "LEMP" program developed in [5]. The channel base return stroke current has a peak value of 50 kA and a maximum time-derivative of 40 kA/µs. The return stroke velocity is assumed to be 1.3 x 10^8 m/s, and the distribution of the return-stroke current along the channel is described by the MTL model [5]. The stroke location is 50 m from the line center and equidistant from the line terminals.

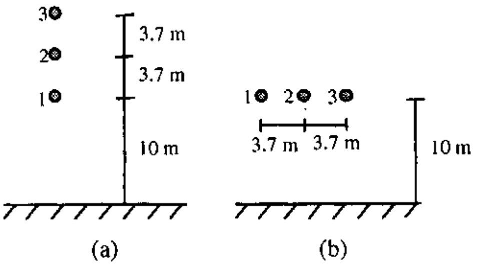

Fig. 1. The two overhead lines in study: (a) vertical configuration, (b) horizontal configuration.

First, let us consider that corona can be represented by a single-phase model (considering that $\gamma_i = 2.0$ for all the conductors) and let us (this second let us could be removed) calculate the induced voltages at the lines extremities. In order to determine the influence of corona, these voltages are compared with those calculated by disregarding corona. In Fig. 2. and Fig. 3, we show the induced voltages calculated for each line configuration. In

Table I we give the ratio between the induced voltage amplitudes on each conductor calculated considering or not corona.

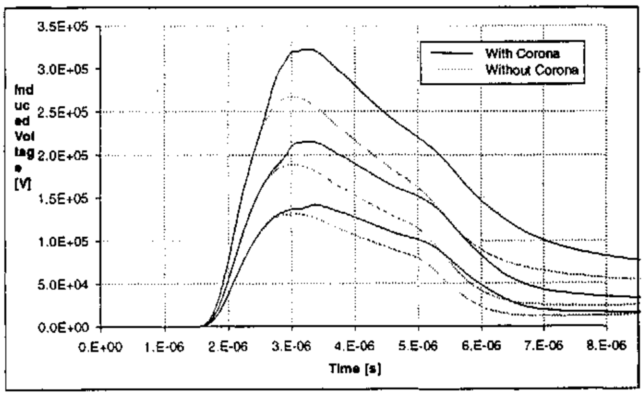

Fig. 2. Voltages induced on each of the vertical configuration line conductors, representing corona by a single-phase model.

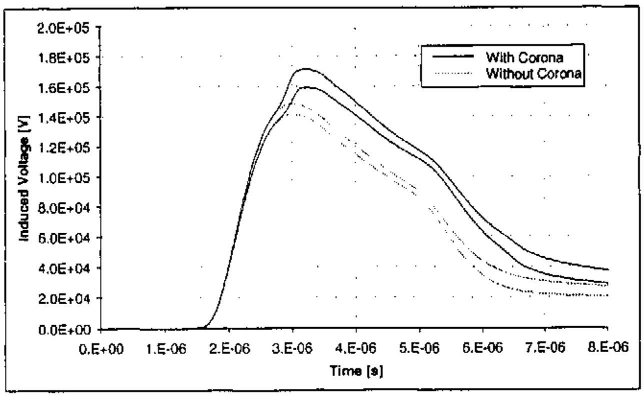

Fig. 3. Voltages induced on each of the horizontal configuration line conductors, representing corona by a single-phase model.

Table I

Ratio between the induced voltage amplitudes obtained considering corona represented by a single-phase model (V_{ci}) and those obtained disregarding corona (V_i).

Ratio	Vertical line	Horizontal line
V_{c1}/V_1	1.08	1.16
V_{c2}/V_2	1.14	1.13
V_{c3}/V_3	1.21	1.16

Table I shows an increase of 8-21% in the voltage amplitudes due to the corona effect at the terminations of the two multiconductor lines. A more severe change of the self capacitance of the conductors, represented by a higher value of γ_i, could lead to even more severe overvoltages. The explanation to this result is the same as in [1].

IV. RESULTS USING MULTI-PHASE CORONA MODEL

In this section, to evaluate the effect of considering the influence of corona on the mutual coupling between conductors, the same calculations of the previous section are performed adopting the new corona model (also with $\gamma_k=2.0$ for each conductor).

In Fig. 5 and in Fig. 6 we show the voltages induced on the vertical and horizontal configuration lines respectively. In Table II we give the ratio between the induced voltage amplitudes obtained considering both corona models for the two line configurations.

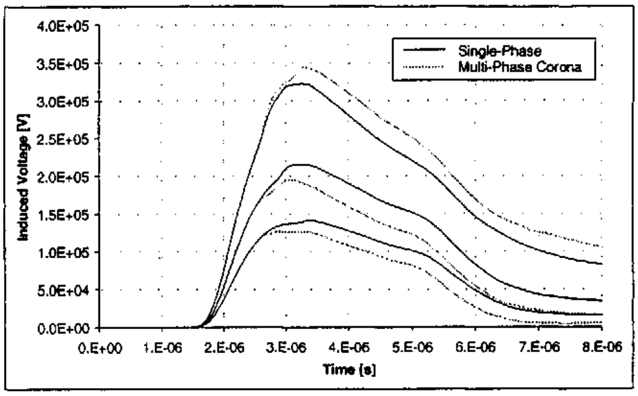

Fig. 4. Voltages induced on the vertical configuration line conductors, representing corona by both models.

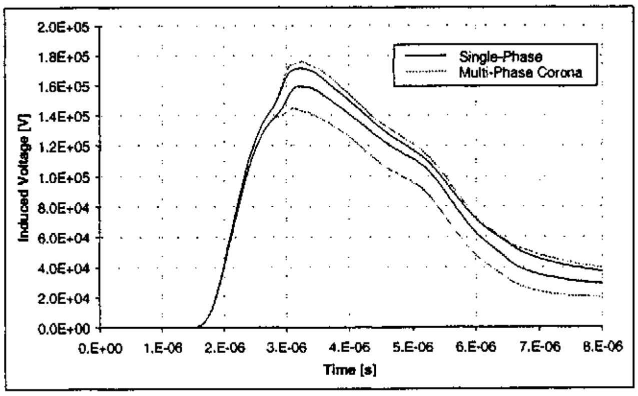

Fig. 5. Voltages induced on the horizontal configuration line conductors, representing corona by both models.

Table II

Ratio between the induced voltage amplitudes considering the multi-phase corona model (V_{cmi}) or single phase corona models (V_{ci}).

Ratio	Vertical line	Horizontal line
V_{cm1}/V_{c1}	0.89	1.03
V_{cm2}/V_{c2}	0.90	0.91
V_{cm3}/V_{c3}	1.07	1.03

As it can be seen from Table II and Fig. *4* and *6*, when considering the influence of corona in the mutual coupling between the conductors more severe overvoltages are obtained for the most exposed conductors while a reduction is obtained for the less exposed ones.

V. CONCLUSIONS

The corona effect in the propagation of lightning-induced voltages on multiconductor overhead power lines was studied, with corona being represented by two different models. As for the case of lightning induced voltages on single conductor overhead power lines, corona produces an increase on the induced voltage amplitudes and on its rise time for multiconductor lines. Although this results still need experimental confirmation and are very dependent on the selected corona model, for the case of severe conditions, as the one presented in this paper (close stroke location and high return-stroke current amplitude), an increase as high as 21% was obtained for the uppermost conductor of the vertical configuration line.

Taking into account the influence of corona on the mutual coupling between conductors can produce even higher increases of the voltage amplitudes in the most exposed conductors, while in the less exposed ones a reduction of the voltage amplitudes is obtained.

VI. ACKNOWLEDGEMENTS

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