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Induced Lightning Disturbances in a Overhead Line

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Abstract: In this research, researchers study the electromagnetic coupling of a lightning wave with an overhead line. The analysis is conducted directly in time domain with hold in account the effect of a finite conductivity of the soil. This analysis calculates the currents and voltages induced at every moment and at every point within the line. To reinforce the theoretical research, researchers present a set of applications that will allow us to validate this analysis.

Key words: Lightning, electromagnetic coupling, overhead line, transient ground resistance, induced voltage

INTRODUCTION

In the power transmission network for optimum distribution of power flows, maintaining the frequency, reactive power compensation, etc., the real-time knowledge of the electrical characteristics of the latter ensures its control and command. This control function and controlling the flow of energy is provided by a set of electronic low levels. If researchers can say that these days, the energy carriers mastered the proper protection of the network against accidental faults this is not the case for protection against lightning (natural defect), especially when an indirect impact. The lightning is a common phenomenon that behaves as a perfect current generator. The ionized lightning channel behaves as a long wire which radiates an electromagnetic field. This field induces in the large ground loop voltages that account kilovolts.

These induced surges can cause damage, as well as the power network monitoring and control electronic networks and transport. This research aims at characterizing overvoltages and overcurrents caused by a wave of lightning on overhead lines after electromagnetic coupling. Researchers model the coupling lightning line by the theory of transmission lines. For electromagnetic excitation which is the second member of the line equations, researchers use the formalism of dipoles taking into account the ground effect for calculating the electromagnetic field radiated by the lightning channel.

EQUATION COUPLING OF A LIGHTNING WAVE WITH AN OVERHEAD LINE

Time-domain single wire overhead line coupling equation without the effect of lossy ground: Equations coupling expressed by Taylor *et al*. (1965) are:

$$\frac{dU(x,t)}{dx} + L\frac{\partial I(x,t)}{\partial t} = -\frac{\partial}{\partial t}\int_0^h B_x^e(x,z,t)dz \quad (1)$$

$$\frac{dI(x,t)}{dx} + C\frac{\partial U(x,t)}{\partial t} = -C\frac{\partial}{\partial t}\int_0^h E_z^e(x,z,t)dz \quad (2)$$

The boundary conditions are:

$$U(0,t) = -Z_A I(0,t) \quad (3)$$

$$U(L,t) = Z_B I(L,t) \quad (4)$$

The equivalent coupling circuit described by Eq. 1 and 2 is shown in Fig. 1.

Time-frequency single wire overhead line coupling equation with the effect of lossy ground: Equations coupling expressed by Taylor *et al*. (1965) are:

$$\frac{dU(x)}{dx} + ZI(x) = -j\omega\int_0^h B_x^e(x,z)dz \quad (5)$$

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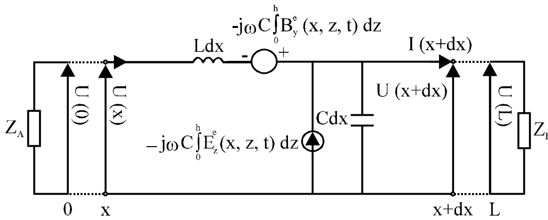

Fig. 1: Equivalent coupling circuit for a lossless single-wire overhead line; without the effect

$$\frac{dI(x)}{dx} + YU(x) = -j\omega C\int_0^h E_z^e(x,z)dz \quad (6)$$

The longitudinal impedance matrix is given by Rachidi *et al.* (1996).

$$Z = j\omega L + Z_w + Z_g \quad (7)$$

Where:
Z_w = The per-unit-length internal impedance of the wire
Z_g = The per-unit-length ground impedance

Transverse admittance matrix by:

$$Y = \frac{(j\omega C)Y_g}{j\beta\omega C + Y_g} \quad (8)$$

Time-domain single wire overhead line coupling equation with the effect of lossy ground: The coupling equation in the time domain is obtained by fourier transformation of the Eq. 5 and 6:

$$\frac{dU(x,t)}{dx} + L\frac{\partial I(x,t)}{\partial t} + \int_0^t Z(t-\tau)I(x,t)d\tau = -\frac{\partial}{\partial t}\int B_Y^e(x,z,t)dz \quad (9)$$

$$\frac{dI(x,t)}{dx} + \int_0^t Y(\tau)U(x,t-\tau)d\tau = -C\frac{\partial}{\partial t}\int_0^h E_z^e(x,z,t) \quad (10)$$

Equation 9 and 10 can be written:

$$\frac{dU(x,t)}{dx} + L\frac{\partial I(x,t)}{\partial t} + \xi_g \otimes \frac{\partial I(x,t)}{\partial t} = -\frac{\partial}{\partial t}\int B_Y^e(x,z,t)dz \quad (11)$$

$$\frac{dI(x,t)}{dx} + C\frac{\partial U(x,t)}{\partial t} = -C\frac{\partial}{\partial t}\int_0^h E_z^e(x,z,t)dz \quad (12)$$

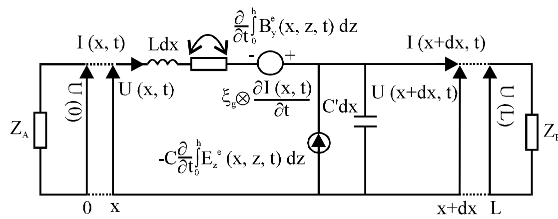

Fig. 2: Equivalent coupling circuit for a lossless single-wire overhead line; with the effect

Where, $\otimes$ is the product of the convolution and transient resistance of the soil as defined (Tesche, 1990):

$$\zeta_g = F^{-1}\left\{\frac{Z_g}{j\omega}\right\} \quad (13)$$

With boundary conditions:

$$U(0,t) = -Z_A I(0,t) \quad (14)$$

$$U(0,t) = -Z_A I(0,t) \quad (15)$$

The coupling circuit equivalent described by the two Eq. 11 and 12 is shown in Fig. 2.

Time-domain multiconductor overhead lines coupling equation with the effect of lossy ground: The coupling equations for the case of an overhead line with multiple conductors can be generalized in time domain as follows (Fig. 3):

$$\frac{d[U_i(x,t)]}{dx} + [L_{ij}]\frac{\partial}{\partial t}[I_i(x,t)] + [\xi_{gij}] \otimes \frac{\partial}{\partial t}[I_i(x,t)] = -\frac{\partial}{\partial t}\left[\int_0^h B_y^e(x,z,t)dz\right] \quad (16)$$

$$\frac{d[I_i(x,t)]}{dx} + [C_{ij}]\frac{\partial}{\partial t}[U_i(x,t)] + [G_{ij}][U_i(x,t)] = -\frac{\partial}{\partial t}[C]\left[\int_0^h E_z^e(x,z,t)dz\right] \quad (17)$$

Where:
$[L_{ij}]$, $[G_{ij}]$ and $[C_{ij}]$ = Matrices inductance, conductance and capacitance per unit length of the line
$[\int_0^h B_y^e$ (x, z, t) dz] = Vectors of the magnetic field
$[\int_0^h B_y^e$ (x, z, t) dz] = Vectors of the electric exciter

The matrix elements $[\xi_{sij}$ (t)] of the ground transient resistance have a singularity when Timotin (1967).

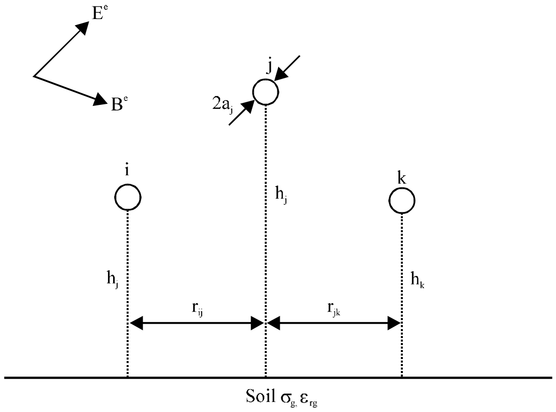

Fig. 3: Geometry of multiconductor lines

Rachidi *et al*. (2003) shows that the expressions of Timotin (1967) is used with excellent approximation when $t > t_{min} = \varepsilon_0 \varepsilon_{rs} / \sigma_s$ and are simplified as follows:

$$\lim_{t\to 0} \zeta_{sii} \approx \frac{\mu_0}{2\pi} \frac{1}{\sqrt{\pi.\tau_{sii} t}} \tag{18}$$

$$\lim_{t\to 0} \zeta_{sij} \approx \frac{\mu_0}{2\pi} \frac{1}{\sqrt{\pi T_{ij} t}} .\cos\left(\frac{\theta_{ij}}{2}\right) \tag{19}$$

EQUATIONS OF LINES BY FINITE DIFFERENCE METHOD

The discretization of Eq. 16 and 17 by finite difference method, consists in subdividing each conductor alternately nodes current and voltage. About 2 consecutive nodes of the same type are separated by an interval Δx in space and $\Delta t/2$ over time. The two ends of the line are defined as nodes voltage (Fig. 4).

The time step and spatial step must verify the stability condition: $v \le \Delta_x/\Delta_t$. Where, v is the speed of propagation of the wave on the line.

Recurrence equations for current and voltage: Discretization of the line equations by finite difference method gives:

$$\left[U_k^{n+1}\right] = \left(\frac{[C]}{\Delta t} + \frac{[G]}{2}\right)^{-1} \left[\left(\frac{[C]}{\Delta t} - \frac{[G]}{2}\right)\left[U_k^n\right] - \left(\frac{\left[I_k^{n+\frac{1}{2}}\right] - \left[I_{k-1}^{n+\frac{1}{2}}\right]}{\Delta x}\right) - [G][h]\frac{\left[E_{z,k}^{n+1}\right] + \left[E_{z,k}^n\right]}{2} - [C][h]\frac{\left[E_{z,k}^{n+1}\right] - \left[E_{z,k}^n\right]}{\Delta t}\right] \tag{20}$$

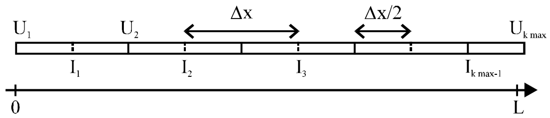

Fig. 4: Schematic spatial discretization of a conductor

$$\frac{[L]}{\Delta t}\left[I_k^{n+\frac{3}{2}}\right] = -\frac{\left[U_{K+1}^{n+1}\right] - \left[U_K^{n+1}\right]}{\Delta x} + [L]\frac{\left[I_k^{n+\frac{1}{2}}\right]}{\Delta t} - \frac{1}{2}\left[\xi_g(\Delta t)\right]\left(\left[I_k^{n+1}\right] - \left[I_k^n\right]\right) - \frac{1}{2}\sum_{j=0}^{n-1}\left\{\begin{bmatrix}\left[\left(\xi_g(n-j)\Delta t\right)\right] + \\ \left[\xi_g\left((n+1-j)\Delta t\right)\right]\end{bmatrix}\left(\left[I_k^{j+1}\right] - \left[I_k^j\right]\right)\right\} - \left(\left[I_k^{n+1}\right] - \left[I_k^{n-1}\right]\right)\left[\xi_g(\Delta t)\right] - [h]\frac{\left[E_{z,k+1}^{n+1}\right] - \left[E_{k,k}^{n+1}\right]}{\Delta x} + \frac{\left[E_{x,k}^{n+1}\right] + \left[E_{x,k}^n\right]}{2} \tag{21}$$

Equations to extremity of the line:

$$\left[U_1^{n+1}\right] = \left(\frac{[C]}{\Delta t} + \frac{[G]}{2}\right)^{-1} \left[\left(\frac{[C]}{\Delta t} - \frac{[G]}{2}\right)\left[U_1^n\right] - \left(\frac{\left[I_1^{n+\frac{1}{2}}\right] - \left[I_0^{n+\frac{1}{2}}\right]}{\Delta x}\right) - [G][h]\frac{\left[E_{x,1}^{n+1}\right] + \left[E_{x,1}^n\right]}{2} - [C][h]\frac{\left[E_{x,1}^{n+1}\right] - \left[E_{x,1}^n\right]}{\Delta t}\right], k = 1 \tag{22}$$

$$\left[U_{k\max}^{n+1}\right] = \left(\frac{[C]}{\Delta t} + \frac{[G]}{2}\right)^{-1} \left[\left(\frac{[C]}{\Delta t} - \frac{[G]}{2}\right)\left[U_{k\max}^n\right] - \left(\frac{\left[I_{k\max}^{n+\frac{1}{2}}\right] - \left[I_{k\max-1}^{n+\frac{1}{2}}\right]}{\Delta x}\right) - [G][h]\frac{\left[E_{x,k\max}^{n+1}\right] + \left[E_{x,k\max}^n\right]}{2} - [C][h]\frac{\left[E_{x,k\max}^{n+1}\right] - \left[E_{x,k\max}^n\right]}{\Delta t}\right], k = k\max \tag{23}$$

APPLICATIONS AND VALIDATIONS

Voltage induced on an overhead conductor: To validate the theoretical research for lightning-line coupling, researchers discuss an application whose results are published by Rachidi *et al*. (2003). Consider an overhead conductor 1 km in length and 9.14 mm radius at a height of 10 m earlier a perfectly conducting ground and finite conductivity. The conductor is assumed to be terminated in its characteristic impedance at both ends. The point of impact is considered symmetrical at both ends and at a distance of 50 m from the conductor (Fig. 5). The electromagnetic field emitted by the lightning wave is calculated using the return stroke to the MTL model (Nucci *et al*., 1988) with a typical value of $V = 1.3\times10^8$ m sec^{-1}, current decay constant factor $\lambda = 1700$ km and expression of Heidler (1985) for the current at the base of the channel with the data in Table 1.

The calculation results Fig. 6, correspond to those published by Rachidi *et al*. (2003) (Fig. 7). A slight difference which is quite predictable because researchers do not take the same value for the characteristic impedance of the conductor (non-value communicated by Rachidi *et al*. (2003).

Voltage induced on a 3-phase overhead line: In this study, researchers consider a 3-phase line length 1 km, illuminated by a lightning wave as presented in Fig. 8. The line is terminated at its ends by its characteristic impedance (Z_c = 461.4 Ω). The point of impact is considered symmetrical at both ends, 50 m from the line. Note that the electromagnetic field emitted by the lightning wave is calculated using the return-stroke current to the MTL model (Nucci *et al*., 1988) with a typical value the velocity $V = 1.9.10^8$ m sec^{-1}, current decay constant factor $\lambda = 1700$ km current and Heidler (1985) expression for the current at the base of the channel with the data of Table 1.

Calculation results that researchers present in this study are those obtained for different configurations of the line (Fig. 9).

In the case of the horizontal and triangle configurations, researchers see that the induced voltages at the extremity of the phase conductors 1 and 3 of the line are identical this confirms the simulation because the 2-phases are excited by the same field electromagnetic calculated middle position. In the configuration vertical, researchers see an increase in the height of the phase conductors causes to an increase in the value of the

Table 1: Lightning parameters

I_1 (kA)	τ_{11} (μ sec)	τ_{21} (μ sec)	n_1	I_2 (kA)	τ_{12} (μ sec)	τ_{22} (μ sec)	n_2
10.7	0.25	2.5	2	6.5	2.1	230	2

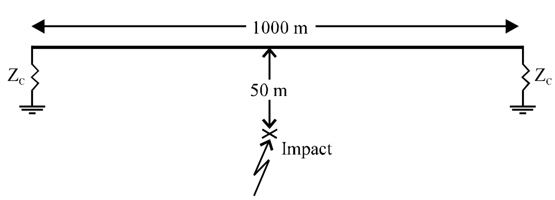

Fig. 5: Line studied

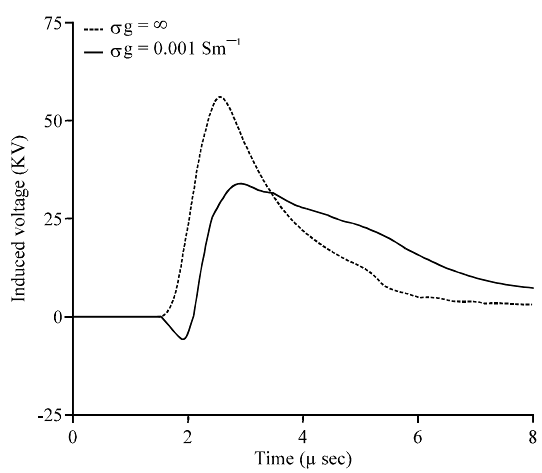

Fig. 6: Voltages induced at the extremity of the conductor

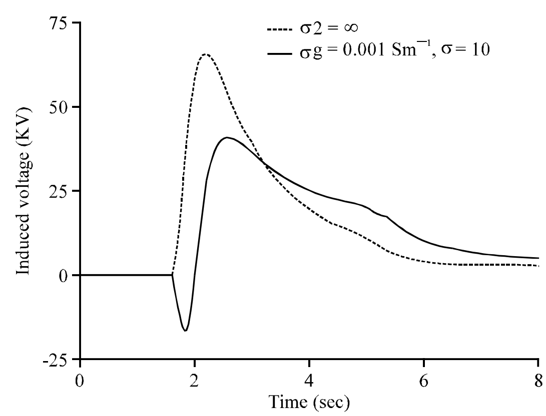

Fig. 7: Voltages induced at the extremity of the conductor by Rachidi *et al*. (2003)

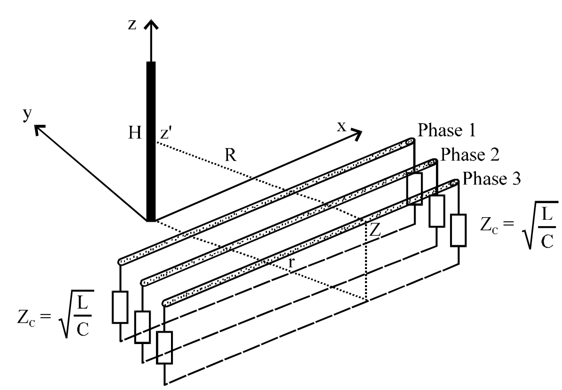

Fig. 8: Configuration of studied

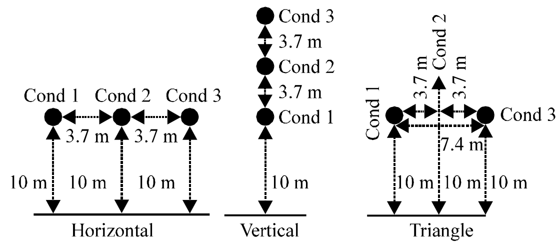

Fig. 9: Different configurations of the line

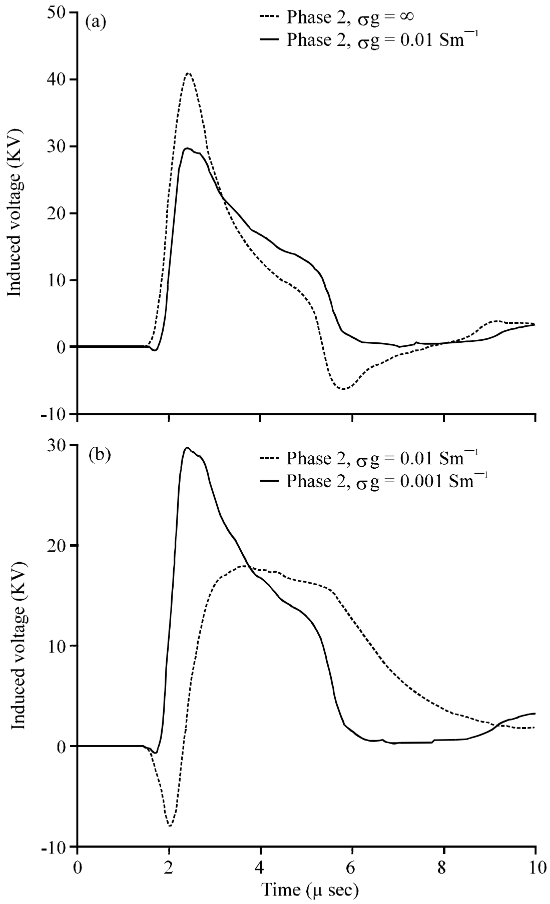

Fig. 10: Voltages induced at the extremity of the line (horizontal line); phase 2

induced voltages. Researchers, also note that the effect of the finite conductivity of the ground is manifested by the appearance of a negative peak and a reduction of the induced voltage due to losses incurred in the line by the finite conductivity of the ground (Fig. 10-16).

Influence of the finite conductivity of the soil: To highlight the effect of the finite conductivity of the ground induced overvoltages, researchers do the calculations for two representative values. These values are: 0.01 and 0.001 Sm^{-1}.

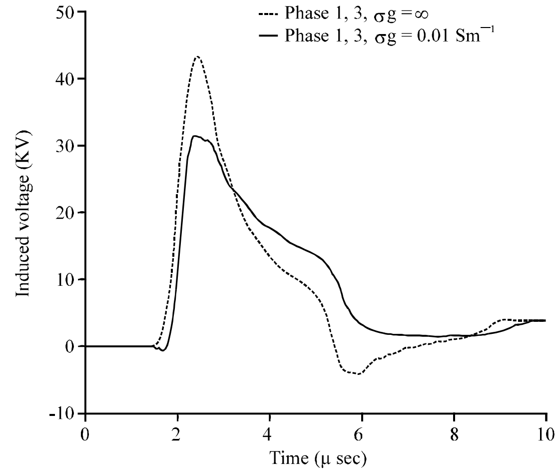

Fig. 11: Voltages induced at the extremity of the line (horizontal line); phase 1 and 3

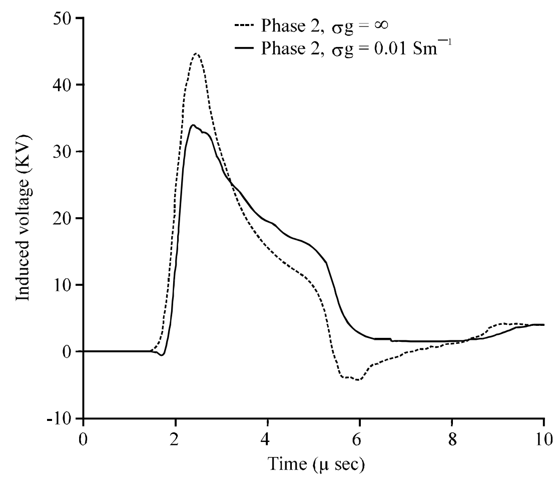

Fig. 12: Voltages induced at the extremity of the line (triangle line); phase 2

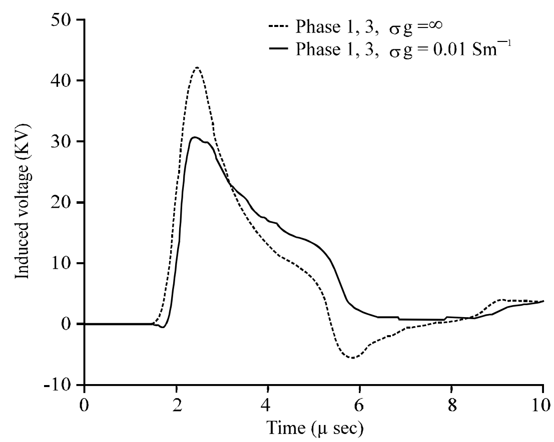

Fig. 13: Voltages induced at the extremity of the line (triangle line); phase 1 and 3

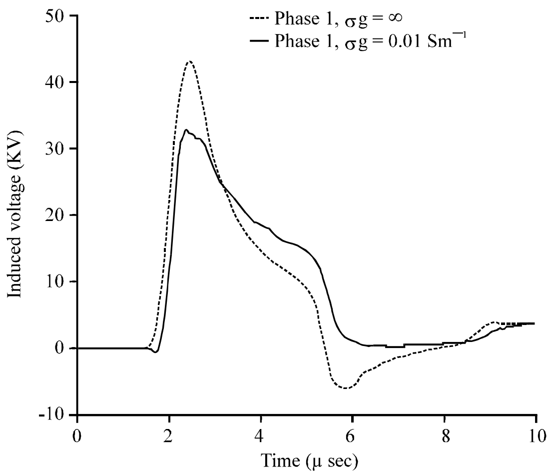

Fig. 14: Voltages induced at the extremity of the line (vertical line); phase 1

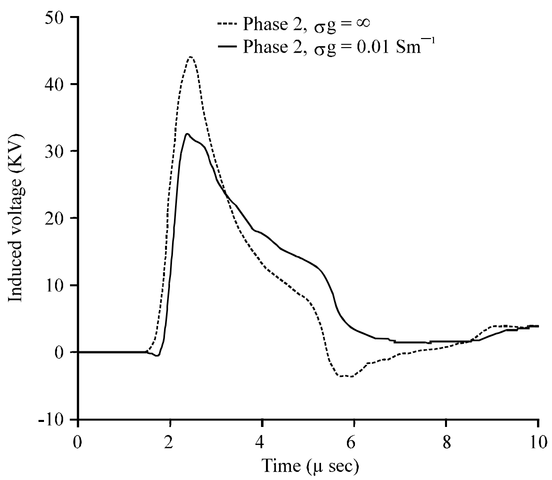

Fig. 15: Voltages induced at the extremity of the line (vertical line); phase 2

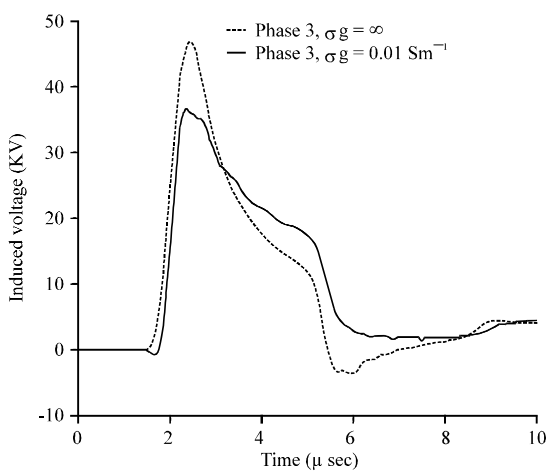

Fig. 16: Voltages induced at the extremity of the line (vertical line); phase 3

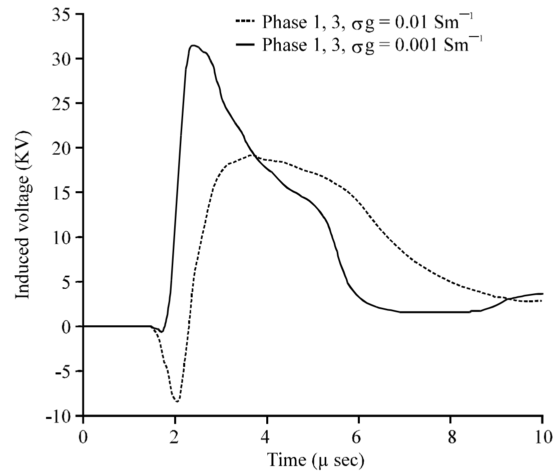

Fig. 17: Voltages induced at the extremity of the line (horizontal line); phase 1 and 3

The results, researchers obtain in Fig. 17, show a decrease in the finite conductivity of the ground causes an increase in negative peak which leads to a significant reduction of the induced voltage.

CONCLUSION

This set of results shows that it is possible to quantify by calculating the electromagnetic effect of lightning on an overhead line that is reflected in the apparition currents and induced voltages. This is an advantage for the insulation coordination and the proper choice of voltage protection. In this research, researchers analyzed the electromagnetic coupling of a lightning wave with an overhead line. This analysis is developed in time-domain from transmission lines equations with second members, taking into account the finite conductivity of the ground and the results are very satisfactory. But that the research is carried out in 2 stages (calculation of the electromagnetic field radiated by the lightning channel and then solving the equations of couplings), its advantages are a simple computer implementation and computation time very low.

REFERENCES

Heidler, F., 1985. Analytische blitzstromfunktion zur LEMP-berechnung. Proceedings of the 18th International Conference on Lightning Protection, September 16-20, 1985, Munich, Germany, pp: 63-66.

Nucci, C.A., C. Mazzetti, F. Rachidi and M. Ianoz, 1988. On lightning return stroke models for LEMP calculations. Proceedings of 19th International Conference on Lightning Protection, April 25-29, 1988, Graz..

Rachidi, F., C.A. Nucci,M. lanoz and C. Mazzetti, 1996. Influence of a lossy ground on lightning-Induced voltages on overhead lines. IEEE Trans. Ctromagnetic Compatib., 38: 250-264.

Rachidi, F., S.L. Loyka, C.A. Nucci and M. lanoz, 2003. A new expression for the ground transient resistance matrix elements of multiconductor overhead transmission lines. Electric Sys. Res., 65: 41-46.

Taylor, C., R. Satterwhite, C. Harrison Jr., 1965. The response of a terminated two-wire transmission line excited by a nonuniform electromagnetic field. IEEE Trans. Antennas Propagation, 13: 987-989.

Tesche, F.M., 1990. On the inclusion of loss in time-domain solutions of electromagnetic interaction problems. IEEE Trans. EMC., 32: 1-4.

Timotin, A., 1967. Longitudinal transient parameters of a unifilar line with ground return. Rev. Roum. Sc. Tech. Electrotech. Energies, 12: 523-535.