Transient Voltages in Transmission Lines Caused by Direct Lightning Strikes

Amilton Soares, Jr., *Member, IEEE*, Marco Aurélio O. Schroeder, and Silvério Visacro, *Member, IEEE*

***Abstract*—This work presents some results concerning the computational simulation of electromagnetic transients in transmission lines caused by direct strikes of lightning. The research has been carried out by application of a hybrid electromagnetic code developed by the authors' research group. The presented results comprise mostly overvoltage waves developed across insulator strings or at ground wires due to the injection of impulsive current at the top of towers and at the shielding wires along span. The effect of adjacent towers on the developed overvoltage is evaluated. Sensitivity analyses are developed considering a range of values for soil resistivity, variable configurations of tower-footing and different injected current waveshapes. Some remarkable conclusions concern the grounding effective length for mitigation of overvoltage across the insulator strings, the relevance of midspan strikes and the importance of accurate representation of lightning current waveshape in the evaluation of lightning performance of lines.**

***Index Terms*—Electromagnetic modeling, overvoltage protection, power system lightning effects, power system transients.**

I. INTRODUCTION

LIGHTNING performance of transmission lines is an issue of major interest for electric utility companies. Nowadays, with increasing requirements for power quality, this matter has been deserving even more attention.

Different methodologies and input data are involved in the calculation of lightning performance of transmission lines: those related to the lightning current itself (e.g., peak value, time-to-crest and rate of rise) [1], those related to the attachment process of lightning channel to transmission lines, and those related to the electromagnetic response of lines due to incoming surges. This work is specifically dedicated to aspects related to the last cited topic.

In a general approach, any insulating gap between an energized and a grounded metallic component of the line may become a path for occurrence of an electric disruption, which may lead to an outage. However, depending on the accuracy of the method employed for calculating the lightning performance of the line, the insulation withstand to overvoltages may be tested for the variety of existing gaps or, in the simpler case, only for those points considered to be more critical (usually in the region where the insulator strings are placed). Anyway, in both approaches, the task requires the modeling of transmission towers, aerial cables (phase and ground wires) and tower-footings.

The objective of this work is to evaluate the resultant overvoltages at transmission lines due to lightning direct strikes. The results are obtained by simulation, considering different conditions of transmission systems and lightning current representation.

II. MODELING OF TRANSMISSION TOWER, AERIAL CABLES AND TOWER-FOOTING

Transmission lines may present several different configurations for towers, aerial cables and tower-footings. These different configurations of line components may establish different responses of the system when it is stressed by lightning, what directly reflects on the resultant values of overvoltage across insulation. The capability of accurately representing this variety of configurations of line components (i.e., the generality of application) is a required feature for the involved models.

Although in some cases the modeling of line components individually has already achieved a remarkable level of accuracy, their simultaneous application in an algorithm for calculation of electromagnetic transients in transmission lines may not be trivial. They may follow different modeling philosophies and, besides that, the mutual electromagnetic coupling among line components should also be considered.

Several models can be found in technical literature to take into account the response of transmission line components against lightning surges. The most traditional ones are related to the aerial cables.

Most works that deal with modeling of transmission towers represent it as a vertical transmission line [2]–[4]. Recent works adopt more complex approaches through, for example, the numerical treatment of field equations [5].

Concerning tower-footing behavior, the grounding low-frequency response is often employed, pondered or not by factors to take into account the soil ionization process for those cases in which high amplitude currents are involved. However, lightning currents present a significant parcel of high frequency components, mainly during the first microseconds of occurrence. It requires from models further considerations, like the variation of soil parameters (resistivity and electrical permitivity) with frequency, the actual current composition in the soil (displacement versus conductive currents) and the mutual coupling

Manuscript received January 21, 2003; revised September 23, 2003. Paper no. TPWRD-00027–2003.

A. Soares, Jr. and S. F. Visacro are with Lightning Research Center (LRC/UFMG-CEMIG), 31270-901, Belo Horizonte, Brazil (e-mail: soaresjr@ieee.org; visacro@cpdee.ufmg.br).

M. A. O. Schroeder is with CEFET-MG, 30510-000, Belo Horizonte, Brazil (schroeder@des.cefetmg.br).

Digital Object Identifier 10.1109/TPWRD.2004.839214

among electrodes. Some works that deal with these cited aspects are [6]–[9].

III. APPLIED ELECTROMAGNETIC MODEL

The model applied in the simulations, called HEM – Hybrid Electromagnetic Model, is derived directly from application of field equations and circuit theory. It is suitable for calculation of electromagnetic transients in configurations of metallic structures (placed in air or soil) that can be represented by a set of cylindrical conductors. Its theoretical basis and details, including the comparison of experimental and simulated results and some applications, can be found in [8]–[12].

Simulations are performed in frequency domain. Time domain response is obtained by application of Fourier Transform. The metallic structure under investigation is partitioned into several cylindrical segments. In each segment, two types of currents are supposed to exist. The longitudinal current $\mathrm{I_L}$ flows along each segment and is supposed to cause voltage drops $\Delta\mathrm{V}$ along all segments of the system. Such voltage drops are calculated applying the magnetic vector potential. The transversal current $\mathrm{I_T}$ flows outward from each segment to the surrounding medium and is supposed to cause potential rises of all segments of the system in relation to infinity. Such potential rises are calculated using the electric scalar potential. The solution of the system for the involved variables, by circuit theory equations, leads to final results.

The electromagnetic behavior of general configurations of metallic structures can be simulated by the model. Input data is limited to the structure geometrical configuration, surrounding media parameters (resistivity, electric permitivity and magnetic permeability) and information about the lightning strike (striking point and current wave). These aspects provide the model with important features: generality of application and combined modeling of tower, aerial cables and tower-footing.

IV. RESULTS AND DISCUSSION

Two main groups of results are here presented. The first one refers to the investigation of the response of a basic line configuration comprising one tower, aerial cables and tower-footing. The second one is related to a more complex system composed of three towers, aerial cables and tower-footing. Non-linear effects (corona and soil ionization) have not been included in this investigation.

According to the version of the model applied in this work, for calculation of the mutual impedance between metallic segments located above ground surface level (in air) the soil has been considered ideal (null resistivity). Electromagnetic coupling between segments placed in different media (air and soil) has not been taken into account.

A. Response of a Basic Configuration: Single Tower, Aerial Cables and Tower-Footing

1) Introduction: The response of the referred system to the injection of an impulsive current wave into the top of the transmission tower has been obtained by simulation. The presence of aerial cables (one ground wire and three phase conductors) and tower-footing has been taken into account. Fig. 1(a) shows the tower configuration and its dimensions. It closely represents some towers used in Brazil, especially for 138 kV systems.

Fig. 1(b) shows the complete simulated system. The aerial cables had their impedances matched at extremities (30 m of distance from tower, at each side), eliminating wave reflections at these points. Tower-footing is composed of grillage and counterpoise cables.

The investigation comprised a large set of simulations, providing sensitivity analyses in relation to several parameters. Soil resistivity values ranged from 100 to 5000 $\Omega\cdot\mathrm{m}$ and each counterpoise length ranged from 0 (absence of cable) to 90 m.

2) Effect of Different Current Waveshapes: A sensitivity analysis of the resultant overvoltage across line insulation to different profiles for the injected lightning current wave front provided some results of interest. Although the concave profile more closely represents the front part of measured lightning current waves, also the ramp and double exponential fronts are frequently adopted. These three different current waveshapes, shown in Fig. 2, were considered by simulation to be injected into the top of the tower under investigation. For comparison purposes, all three waves present the same time-to-crest (5 μs) and maximum amplitude (1 kA). After current peak, the waves decay linearly, reaching 50% of peak (0.5 kA) in 50 μs.

Equations for the current wavefront are ("I" in kA, "t" in seconds)

- Ramp:

$$I(t) = \alpha_1 t. \tag{1}$$

- Concave:

$$I(t) = \frac{\left[\exp\left(\frac{\alpha_2 t}{t_f}\right) - 1\right]}{\left[\exp(\alpha_2) - 1\right]}. \tag{2}$$

- Double Exp.:

$$I(t) = I_p(\exp(\alpha_3 t) - \exp(\alpha_4 t)). \tag{3}$$

$\alpha_1 = 2.0 \times 10^5\ \mathrm{kA}\cdot\mathrm{s}^{-1}$; $\alpha_2 = 1.88$; $\alpha_3 = -6.0 \times 10^3\ \mathrm{s}^{-1}$; $\alpha_4 = -1.05 \times 10^6\ \mathrm{s}^{-1}$; $I_p = 1.036$ kA and $\mathrm{t_f} = 5\ \mu$s.

Fig. 3 presents the resultant overvoltage across the lower insulator string, for each injected current wave. For this case, tower-footing configuration is composed of grillage plus counterpoise cables (50 m long each leg). Soil resistivity is assumed as 500 $\Omega\cdot\mathrm{m}$. Quite different wave profiles and voltage peaks are observed for the double exponential, ramp and concave responses. Results related to other values of counterpoise length and soil resistivity follow the same pattern.

After 5 μs, the trend of all three curves is to reach the same amplitude, once the current waves become similar after this instant of time.

These results have shown the importance of using representative current waveshapes for calculation of voltages caused by direct strikes. Once insulation coordination analyses are highly dependent on the resultant overvoltage peak and waveshape, the choice of a nonrepresentative lightning current waveshape may consequently lead to nonrepresentative results.

3) Effect of Counterpoise Length and Soil Resistivity: The following analysis is related to the effect of mitigating the overvoltage across the insulator strings by acting on the grounding

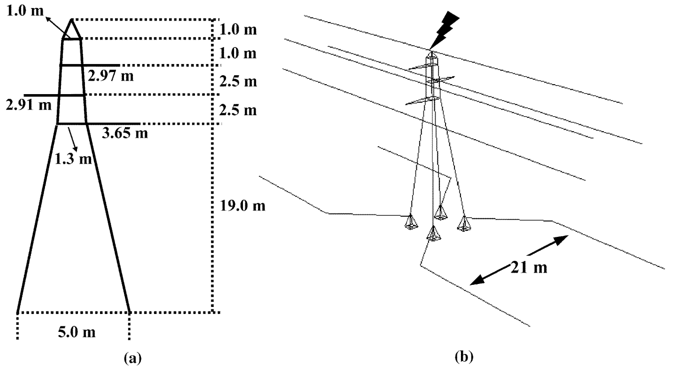

Fig. 1. (a) Tower configuration and dimensions (side view) and (b) simulated structure—transmission tower, aerial cables, and tower-footing.

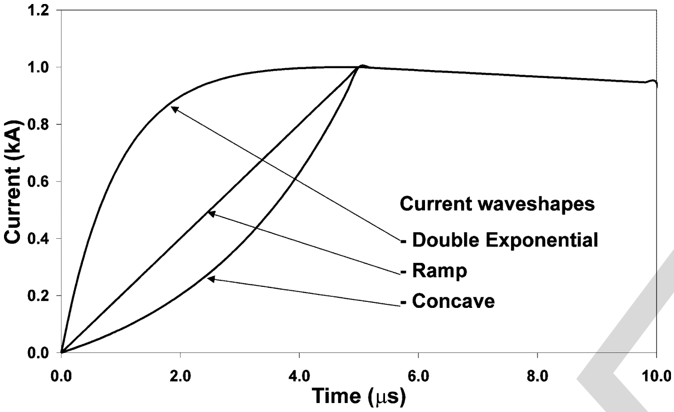

Fig. 2. Current waveshapes considered to be injected (by simulation) into tower top.

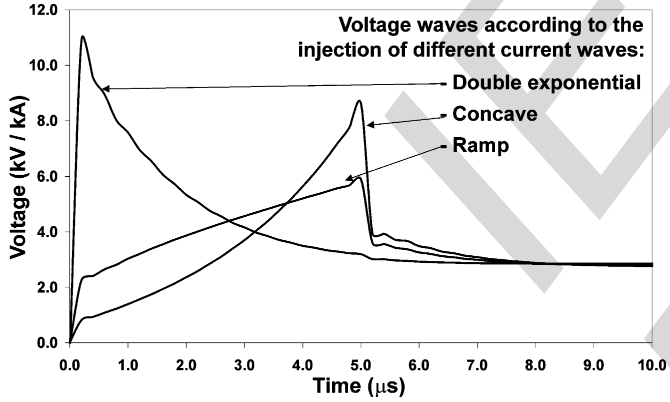

Fig. 3. Resultant overvoltage waveshapes across the lower insulator string due to injection of different current waveshapes on tower top.

configuration. Fig. 4 shows the resultant voltage waves across the lower insulator string obtained for different lengths of counterpoise cable: 0, 10, 30, 50, 70 and 90 m. Soil resistivity was considered to be $100\ \Omega\cdot\mathrm{m}$, and injection of a concave type current wave (amplitude of 1 kA, time-to-crest of 5 μs) was considered to take place on the top of the tower.

Fig. 5 presents the same situation of current injection and tower-footing configuration as before, but for a $2000\ \Omega\cdot\mathrm{m}$ soil.

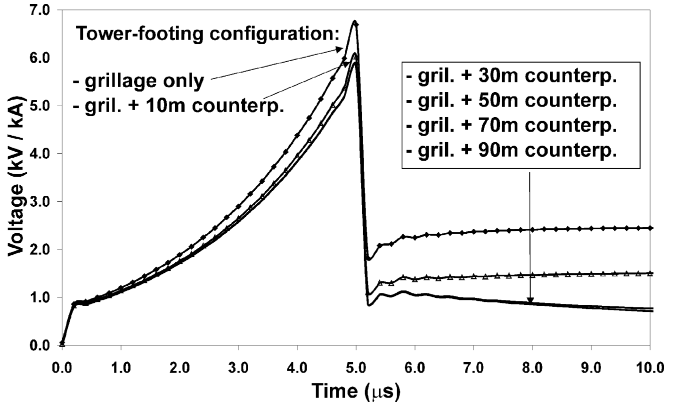

Fig. 4. Voltage waves across lower insulator string for a $100\ \Omega\cdot\mathrm{m}$ resistive soil, for different values of counterpoise length.

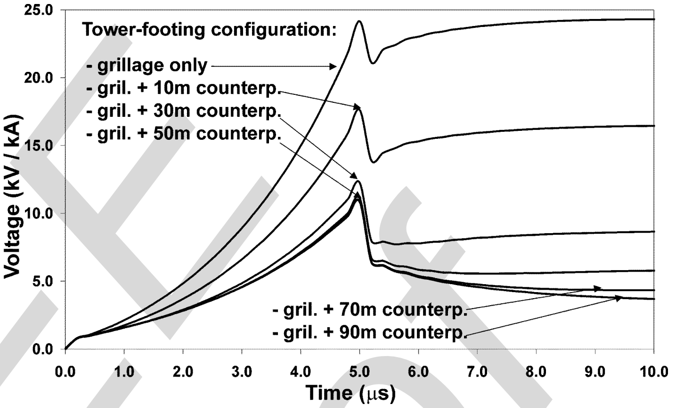

Fig. 5. Voltage waves across lower insulator string for a $2000\ \Omega\cdot\mathrm{m}$ resistive soil, for different values of counterpoise length.

In both cases, it is clear the effectiveness of increasing counterpoise length in order to mitigate the voltage peak across the insulator string. However, this effect is more pronounced for the $2000\ \Omega\cdot\mathrm{m}$ soil, as the relative decrease of ground impedance is larger in this case.

Voltage waves crest, in Figs. 4 and 5, happen in 5 μs (following the injected current crest time). After this, the system response is mostly defined by its low frequency response, what makes curve amplitudes tend to be approximately proportional to tower-footing resistance.

The results show that the increase of counterpoise length is not capable of decreasing voltage peak indefinitely. A minimum voltage level is reached beyond which no further mitigation is possible by counterpoise length control. For each value of soil resistivity, the minimum length of counterpoise cable capable of providing the maximum voltage mitigation level is associated to the so-called "grounding effective length". Lower values of voltage are not reached by use of counterpoise cables longer than the effective length, for the considered conditions in simulations. Thus, their use would be meaningless (considering lightning performance purposes). Less conductive soils require longer cables for effective length achievement.

For the presented cases, cable effective lengths are around 10 m for the $100\ \Omega\cdot\mathrm{m}$ soil and 50 m for the $2000\ \Omega\cdot\mathrm{m}$ soil. More accurate results can be obtained by simulations using smaller steps of counterpoise length.

4) Voltage Across Upper, Middle and Lower Insulator Strings: Figs. 6 and 7 present the resultant voltages across upper, middle and lower insulator strings (ramp-type current wave injected – see Fig. 2), respectively for a 100 $\Omega \cdot \mathrm{m}$ and a 2000 $\Omega \cdot \mathrm{m}$ soil. In both cases, tower-footing configuration comprised grillage plus 50 m long counterpoise cables.

Around 0.2 μs, the voltage curves present a break in the fast rising tendency, caused by the arrival of the voltage wave reflected at tower-footing. In both figures, curves regarding the same insulator show coincident voltage amplitudes when it occurs. At this moment, the upper insulator string presents higher voltage values, once it is the first to suffer the incident wave stress and, additionally, the voltage wave reflected at tower base takes a longer time to reach it.

On the other hand, after 5 μs voltage curves present an opposite behavior. Once in this period the voltage along tower is approximately uniform (low frequency phenomenon) and considering that the electromagnetic coupling between ground wire and lower phase cable is weaker than with the upper ones, voltage across the lower insulator keeps higher values.

The remaining analysis should contemplate the comparison of voltage wave peak values. The relation among voltages across insulator strings depends on tower-footing impulsive behavior. Higher values for this parameter (high resistivity soils and short counterpoises) cause voltage across lower insulator string to show a higher peak value than across the upper one. Lower values of grounding surge impedance cause voltage across the upper one to be higher. This analysis is confirmed by the behavior of curves in Figs. 6 and 7.

B. Response of a System Comprising Three Towers, Aerial Cables and Tower-Footing

1) Introduction: In order to evaluate the influence of adjacent towers and lightning strikes along the span, a larger system has been investigated. The simulated configuration comprised three towers (300 m span between towers), aerial cables and tower-footings, like schematically shown in Fig. 8. The configurations of towers and aerial cables are the same of those used in the previous section (same level of detail even for the adjacent towers – see Fig. 1(b)). Conductor sags have not been considered. At the extremities, aerial cables had their impedances matched in order to eliminate wave reflection. Differently from previous section, in the present case tower-footing has been represented by one meter deep vertical rods (four rods per tower), embedded in a 100 $\Omega \cdot \mathrm{m}$ soil.

Different current injection points into the ground wire have been considered: top of the central tower, ¼ of span and ½ of span (midspan). Resultant overvoltages at these same nodes have been evaluated. In this investigation, the concave type current wave has been used, with peak of 1 kA.

2) Strike on the Top of Central Tower (Presence Versus Absence of Adjacent Tower): Figs. 9 and 10 show the resultant overvoltage on the top of the central tower (for current injection at this point), considering and not considering the presence of the adjacent towers. Fig. 9 refers to the injection of a current wave with time-to-crest of 5 μs and Fig. 10 to a current wave with time-to-crest of 1.5 μs.

A 300 m span corresponds to a travel time of 1 μs (wave traveling at light velocity). It means that the voltage waves reflected at adjacent towers take 2 μs to arrive at the top of the central one. In Fig. 10, the current time-to-crest instant happens before 2 μs and, consequently, the voltage peak is not affected by the presence of adjacent towers.

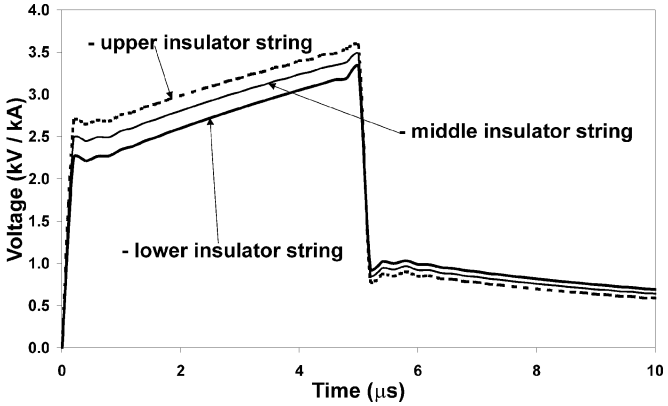

Fig. 6. Voltage waves across upper, middle and lower insulator strings for a 100 $\Omega \cdot \mathrm{m}$ resistive soil and 50 m long counterpoises.

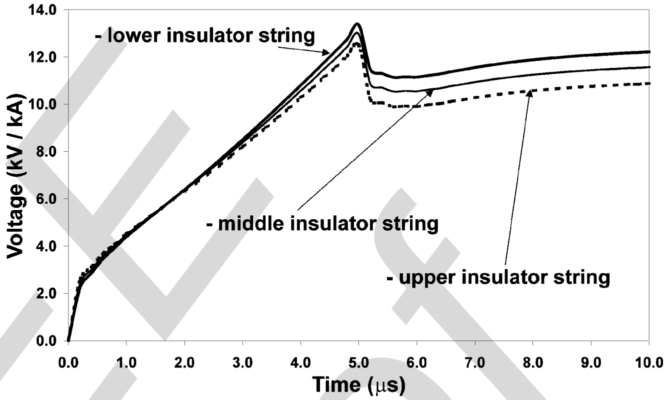

Fig. 7. Voltage waves across upper, middle and lower insulator strings for a 2000 $\Omega \cdot \mathrm{m}$ resistive soil and 50 m long counterpoises.

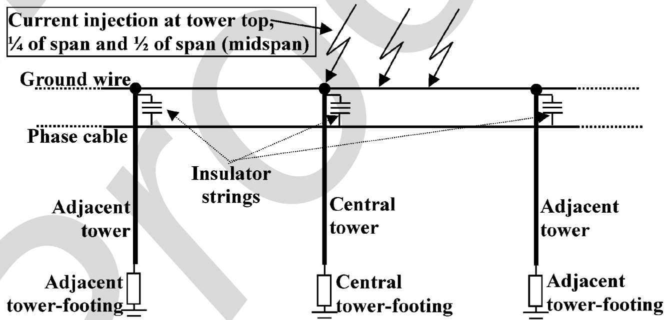

Fig. 8. Scheme of simulated configuration, comprising three towers, aerial cables and tower-footing.

On the other hand, for the case illustrated in Fig. 9, injected current time-to-crest is greater than 2 μs, and thus voltage peak value is affected by wave reflections at adjacent towers. For this case, the presence of such towers mitigated moderately the voltage on tower top. In a conservative or initial approach the adjacent towers may be neglected, for the simulated conditions.

3) Strike on the Top of Central Tower (Resultant Voltage Waves at Ground Wire Along Span and at Phase Cables): The resultant voltage waves at the ground wire along span for current injection on the top of the central tower is shown in Fig. 11 (time-to-crest of injected current wave: 5 μs). Higher values

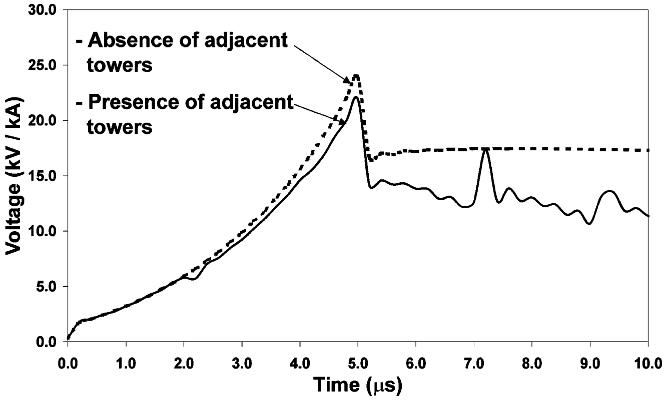

Fig. 9. Resultant overvoltages on the top of central tower (for current injection at this point) – time-to-crest of injected current: 5 μs.

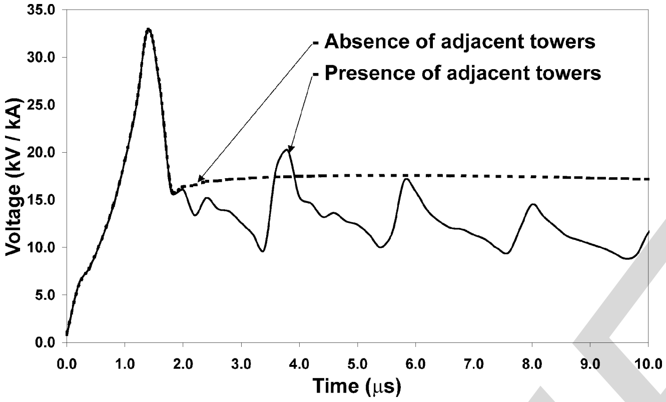

Fig. 10. Resultant overvoltages on the top of central tower (for current injection at this point) – time-to-crest of injected current: 1.5 μs.

of overvoltage are developed close to the current injection point. Voltages at the other nodes keep lower values, not only caused by wave attenuation but mostly because they are more influenced by voltage reflection at adjacent towers.

Fig. 12 illustrates the resultant voltage waves at phase conductors, close to the central tower, for the same condition of incidence of Fig. 11. Resultant voltage waveforms at phase cables are similar to the voltage waveform on tower-top, but with lower amplitudes, due to different levels of coupling.

4) Strike on Ground Wire at Midspan (Resultant Voltage Waves at Ground Wire Along the Span): Fig. 13 shows the resultant overvoltage waves at ground wire at 1/2 of span (midspan), 1/4 of span and at central tower top, for injection of current at midspan.

For such occurrence, considerably higher voltages are developed at midspan in relation to other points along the cable. In comparison with the maximum voltage observed for strike at the tower top (Fig. 11), the voltage peak at midspan, in this case, is approximately three times higher.

Some algorithms for calculation of the lightning performance of transmission lines do not consider the probability of occurrence of backflashovers at this region (midspan). Results of Fig. 13 suggest this evaluation may be included in these calculations, especially for fast front lightning currents. Voltage close to tower reveals moderate values, because of the proximity to the connection to earth.

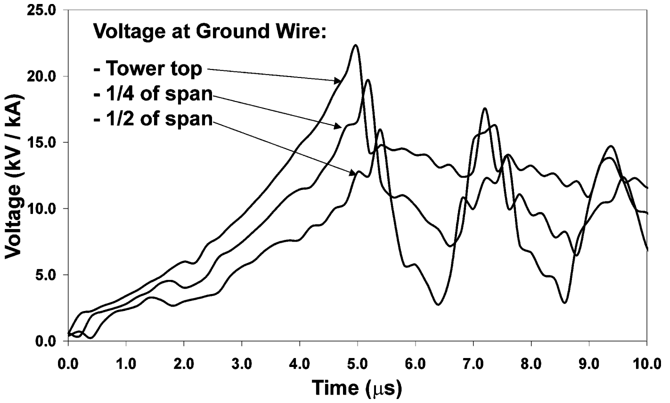

Fig. 11. Voltages at ground wire along the span for current injection on the top of the central tower.

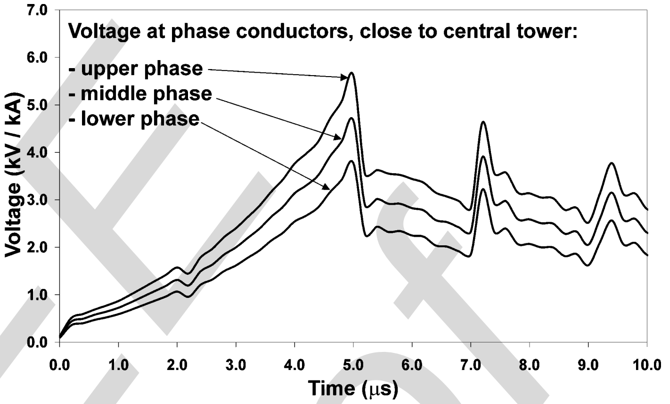

Fig. 12. Voltages at the phase cables, close to the central tower, for current injection on the top of the central tower.

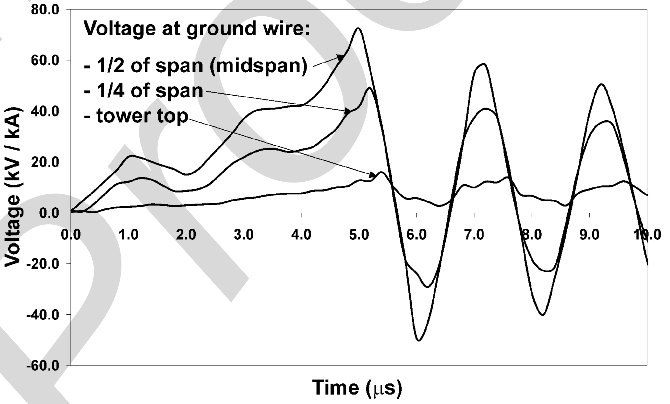

Fig. 13. Voltages at ground wire along span for current injection at midspan.

V. CONCLUSION

This work presented results concerning the response of some transmission line configurations against lightning, obtained by application of a hybrid electromagnetic model (HEM). The main characteristic of such model is its generality of application: general configurations of metallic structures, aerial or buried, can be simulated. The required input data comprise only system geometrical configuration, media parameters and lightning strike parameters. No further assumptions (e.g., coupling coefficients or surge impedances), are required.

The importance of accurate representation of the incident lightning current wave has been denoted. Resultant overvoltage waveshapes across insulator strings may present quite diverse profiles for different current wavefronts.

Simulations considering varying lengths for the counterpoise cable and different values of soil resistivity denoted the effectiveness of increasing counterpoise cable in order to mitigate resultant overvoltages across insulators, until the grounding effective length is achieved. Besides that, it has been shown that the highest overvoltage amplitude may develop across upper or lower insulator strings, depending on tower-footing impulsive behavior.

Simulation of a transmission line configuration revealed only a moderate influence of adjacent towers on the mitigation of the resultant overvoltage at the central tower, for the investigated case. Midspan strikes caused large values of overvoltage, indicating that, in a general approach, this kind of strike may not be neglected by algorithms for calculation of lightning performance of transmission lines, especially for fast front lightning currents.

REFERENCES

[1] M. A. O. Schroeder, A. Soares Jr., S. F. Visacro, L. C. L. Cherchiglia, V. J. Souza, J. H. Diniz, and A. M. Carvalho, "Evaluation of directly measured lightning parameters," in *Proc. 1999 Int. Symp. Lightning Protection (V SIPDA)*, pp. 7–11.

[2] M. A. Sargent and M. Darveniza, "The calculation of double circuit outage rate of transmission lines," *IEEE Trans. Power Applicat. Syst.*, vol. PAS-88, no. 5, pp. 680–687, May 1969.

[3] W. A. Chisholm, Y. L. Chow, and K. D. Srivastava, "Travel time of transmission towers," *IEEE Trans. Power Applicat. Syst.*, vol. PAS-104, no. 10, pp. 2922–2928, Oct. 1985.

[4] M. T. C. Barros and M. E. Almeida, "Computation of electromagnetic transients on nonuniform transmission lines," *IEEE Trans. Power Delivery*, vol. 11, pp. 1082–1091, Apr. 1996.

[5] Y. Baba and M. Ishii, "Analytical and experimental study on surge response of transmission tower," *IEEE Trans. Power Delivery*, vol. 15, pp. 812–819, Apr. 2000.

[6] S. F. Visacro, "An overview on grounding modeling," in *Proc. 1998 Int. Conf. Grounding and Earthing (GROUND'98)*, pp. 41–46.

[7] E. E. Oettlé, "A new general estimation curve for predicting the impulse impedance of concentrated earth electrodes," *IEEE Trans. Power Delivery*, vol. 3, pp. 2020–2029, Oct. 1987.

[8] S. F. Visacro and C. M. Portela, "Modeling of earthing systems for lightning protection applications, including propagation effects," in *Proc. 1992 Int. Conf. Lightning Protection (XXI ICLP)*.

[9] A. Soares Jr. *et al.*, "Investigation concerning CEMIG's transmission system tower-footing configurations aiming the improvement of the lightning performance of lines" (in Portuguese), in *1997 Proc. IV SIPDA*.

[10] S. F. Visacro, A. Soares Jr., M. H. M. Vale, and M. A. O. Schroeder, "Evaluation of current and potential distribution for lightning protection system including the behavior of grounding electrodes," in *Proc. 2000 Int. Conf. Lightning Protection (XXV ICLP)*.

[11] S. F. Visacro, A. Soares Jr., and M. A. O. Schroeder, "An interactive computational code for simulation of transient behavior of electric system components for lightning currents," in *Proc. 2002 Int. Conf. Lightning Protection (XXVI ICLP)*.

[12] A. Soares Jr., M. A. O. Schroeder, and S. F. Visacro, "Application of an electromagnetic model for calculation of transient voltages in transmission towers," in *Proc. 2002 Int. Conf. Lightning Protection (XXVI ICLP)*.

Amilton Soares J. (S'97–M'02) was born in Belo Horizonte, Brazil, in 1972. He received the B.Sc., M.Sc., and Dr.Sc. degrees in electrical engineering from the Federal University of Minas Gerais (UFMG), Brazil, in 1994, 1996, and 2001, respectively.

He is presently an Associate Researcher of the Lightning Research Center (LRC), Brazil, and his areas of interest are electromagnetic modeling, electromagnetic transients, and lightning performance of transmission lines.

Marco Aurélio O. Schroeder was born in Cataguases, Brazil, in 1968. He received the B.Sc. in electrical engineering from the Catholic University of Petropolis, Brazil, in 1991, and the M.Sc. and Dr.Sc degrees in electrical engineering from the Federal University of Minas Gerais, Brazil, in 1996 and 2001, respectively.

In 2001, he joined University of Belo Horizonte as Professor and Researcher. His areas of interest are electromagnetic modeling and lightning current measurement.

Silvério Visacro F. (M'00) was born in Belo Horizonte, Brazil, in 1956. He received the B.Sc. in 1980 and his M.Sc. in 1984, in electrical engineering, from UFMG. In 1992, he received the doctor degree from the Federal University of Rio de Janeiro.

Since 1980 he has been with UFMG as Professor in Applied Electromagnetics. EM modeling, lightning, and grounding are his special fields of interest. Currently, he is the Head of the Lightning Research Center, an investigation institution created by cooperation between UFMG and CEMIG.