Computation of Lightning Overvoltages using Nonuniform, Single-Phase Line Model

M. S. Mamis and M. Koksal

Department of Electrical and Electronics Engineering
Inonu University, 44069-Malatya, Turkey
e-mail: smamis@inonu.edu.tr
mkoksal@inonu.edu.tr

Abstract - **An s-domain method for the analysis of lightning transients on transmission lines is presented. Transmission tower is considered as a nonuniform line and it is divided into adequate number of sections which are then assumed uniform. The terminal equation for the nonuniform line is calculated by using the terminal equations of the uniform line sections. By using the boundary conditions, total response of the system in s-domain is obtained. Fast inverse Laplace transform is used for frequency to time domain conversion. The method is applied for the calculation of transmission tower lightning surge response. The effect of frequency dependent parameters is included.**

Keywords: Lightning Overvoltages, Nonuniform Line, Fast Inverse Laplace Transform.

I. INTRODUCTION

In the power transmission and distribution networks, if the distance between the line and ground varies, the change of line parameters is nonuniform. Steel line tower is an example for the nonuniform lines. Modeling and analysis of nonuniform lines in complex frequency (s) or time (t) domain has become important recently and very little work has appeared in the literature about this subject [1-5].

The method presented in this paper uses s-domain for the analysis of nonuniform lines. The line having space-dependent parameters is divided into adequate number of sections and the parameters of each section are approximated by uniform parameters. By this approach, terminal equations of uniform sections involving hyperbolic equations are used to calculate a terminal equation for the whole nonuniform line in s-domain. By the proposed method, nonuniform lines having arbitrary variation can be easily simulated and transmission line losses and frequency dependence of parameters can also be included into the analysis.

II. TRANSMISSION LINE MODELING FOR LIGHTNING SURGE ANALYSIS

A transmission system is composed of phase conductors, earth wires and transmission towers. Most of the lightning strokes are indirect strokes (strokes on towers and earth wires) in the transmission systems. Accurate modeling of the system is required for the accurate computation of lightning surge transients. Frequency dependence of line parameters and nonuniform variation of tower parameters have to be considered in the calculations.

A. Terminal Equations of Uniform Line

Four electrical characteristics (resistance, inductance, conductance and capacitance) of a uniform transmission line are distributed uniformly along the line. The voltage and current wave propagation along the line (at a point x) are related to the line's distributed resistance r (per unit length), inductance l, conductance g and capacitance c, by the generalized telegrapher's equations

$$-\frac{\partial v(x,t)}{\partial x} = r i(x,t) + l\frac{\partial i(x,t)}{\partial t}, \qquad (1a)$$

$$-\frac{\partial i(x,t)}{\partial x} = g v(x,t) + c\frac{\partial v(x,t)}{\partial t}. \qquad (1b)$$

The solution of the above equations for terminal voltages and currents of uniform line shown in Fig. 1 can be easily obtained in frequency domain as

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \cosh\gamma\ell & Z_0\sinh\gamma\ell \\ Z_0^{-1}\sinh\gamma\ell & \cosh\gamma\ell \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}, \qquad (2)$$

where the subscripts R and S stand for the receiving and the sending ends, respectively, and ℓ is the total line length; V_S (V_R) and I_S (I_R) are the voltage and current phasors of the sending (receiving) ends [6]. Further, Z_0 and γ are complex characteristic impedance and propagation constant, respectively, and they are defined by $Z_0 = \sqrt{Z/Y}$, $\gamma = \sqrt{ZY}$.

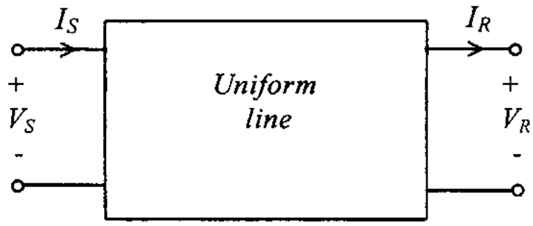

Fig. 1. Uniform transmission line.

In the case of frequency dependent transmission line the series impedance Z is expressed by [7]

$$Z = Z_i + \frac{j\omega\mu_o}{2\pi}\ln\frac{2(h+p)}{r}\ \Omega/\text{m}, \qquad (3)$$

where $p = 1/\sqrt{j\omega\mu_0\sigma}$ is the complex penetration depth; h is the conductor height above ground, r is the conductor radius, σ is the earth conductivity, and Z_i is the d.c. resistance of the conductor.

B. Terminal Equations of Nonuniform Line

For the lightning surge analysis, transmission towers are modeled by nonuniform lines. It is not possible to obtain analytical solutions for a nonuniform line with arbitrary space varying parameters. For this reason nonuniform transmission line is considered as cascaded connection of uniform sections as shown in Fig. 2. Since the terminal equations of each section can be found even for the lossy and frequency dependent cases, the terminal equations of the whole line and hence the response of the system involving such a line can be calculated easily.

Rewriting (2) for the i-th section having series impedance $Z_i = r_i + sl_i$ and shunt conductance $Y_i = g_i + sc_i$, we obtain

$$\begin{bmatrix} V_{Si} \\ I_{Si} \end{bmatrix} = \begin{bmatrix} \cosh\gamma_i\ell_i & Z_{oi}\sinh\gamma_i\ell_i \\ Z_{oi}^{-1}\sinh\gamma_i\ell_i & \cosh\gamma_i\ell_i \end{bmatrix}\begin{bmatrix} V_{Ri} \\ I_{Ri} \end{bmatrix}, \qquad (4)$$

where $Z_{oi} = \sqrt{Z_i/Y_i}$ and $\gamma_{oi} = \sqrt{Z_i Y_i}$ are the characteristic impedance and propagation coefficient of the i-th section, respectively; and ℓ_i is the length of this section starting from $x=x_i$ and ending at $x=x_{i+1}$. The constant resistance parameter r_i of the i-th section is chosen as the arithmetic mean of the values of the space dependent resistance $r(x)$ of the line at the end points of this section; i.e.

$$r_i = \frac{r(x_i) + r(x_{i+1})}{2}. \qquad (5)$$

Other parameters l_i, g_i and c_i can be calculated in the same manner.

Equation (4) can be written in the compact form as

$$S_i = H_i R_i, \qquad (6)$$

where

$$S_i = \begin{bmatrix} V_{Si} \\ I_{Si} \end{bmatrix}, \qquad (7a)$$

$$\mathrm{H_i} = \begin{bmatrix} \cosh\gamma_i\ell_i & Z_{oi}\sinh\gamma_i\ell_i \\ Z_{oi}^{-1}\sinh\gamma_i\ell_i & \cosh\gamma_i\ell_i \end{bmatrix}, \qquad (7b)$$

and

$$\mathrm{R_i} = \begin{bmatrix} V_{Ri} \\ I_{Ri} \end{bmatrix}. \qquad (7c)$$

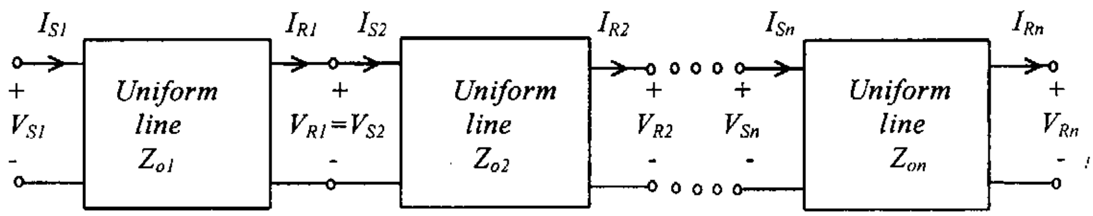

Fig. 2. Nonuniform transmission line as the cascaded connection of uniform line sections.

Since the receiving-end quantities of the i-th section are sending-end quantities for the $(i+1)$-th section, we can write

$$R_i = S_{i+1} = H_{i+1}R_{i+1}. \qquad (8)$$

By using the relations in (7) and (8), the following terminal equation can be written for the whole line

$$S_1 = (H_1 H_2 \cdots H_n)R_n. \qquad (9)$$

Since the sending-end (receiving-end) of the first (last) section is the sending-end (receiving-end) of the actual line, we can write the terminal equations of the whole line as

$$S = HR; \qquad (10)$$

where

$$S = S_1 = \begin{bmatrix} V_S \\ I_S \end{bmatrix}, \qquad (11a)$$

$$\mathrm{R} = \mathrm{R}_1 = \begin{bmatrix} V_R \\ I_R \end{bmatrix}, \qquad (11b)$$

$$H = H_1 H_2 \cdots H_n \qquad (11c)$$

are the sending-end and receiving-end terminal variables, and H is the terminal coefficient matrix of the line. Once (10) is calculated for any frequency $s=\sigma+j\omega$, voltages and currents at the terminals of the line at that frequency can be calculated by considering the boundary conditions.

C. Fast Inverse Laplace Transform

Many algorithms for the numerical computation of the inverse Laplace transform are found in the literature. For a fast frequency to time domain conversion, the algorithm developed by Hosono [8] has been selected for its accuracy, efficiency, and ease of implementation; due to these properties this method is known to be Fast Inverse Laplace Transform (FILT) [2]. Laplace inversion formula for a function $F(s)$ is

$$f(t) = \frac{1}{2\pi j}\int_{\gamma+j\omega}^{\gamma+j\omega} F(s)\exp(st)ds. \qquad (12)$$

For evaluation of the inverse Laplace transform numerically, Hosono used an approximation for $exp(s)$ as

$$e^s = \frac{e^a}{2\cosh(a-s)}$$
$$= e^s - e^{-2a}e^{3s} + e^{-4a}e^{5s} + \cdots \qquad (13)$$

where a is a sufficiently large real constant; i.e. $a \gg 1$. Using (13), the inverse Laplace transform in (12) is approximated by

$$f(t) = (e^a/t)(F_1 + F_2 + F_3 + \cdots), \qquad (14)$$

where

$$F_n = (-1)^n \operatorname{Im} F\{[a + j(n-0.5)\pi]/t\}. \qquad (15)$$

Retaining the first $(k-1)$ terms of the infinite series in Eq. 14 and applying the Euler transformation on the rest, the following finite series which is used for fast inverse Laplace transform is obtained;

$$f(t) = (e^a/t)\left[\sum_{n=1}^{k-1} F_n + (1/2^{p+1})\sum_{n=0}^{p} A_{pn}F_{k+n}\right]. \qquad (16)$$

The truncation coefficients A_{pn} are defined recursively by

$$A_{mm} = 1, \quad A_{mn-1} = A_{mn} + \binom{m+1}{n} \qquad (17)$$

where the last term denotes combinations.

To obtain the time domain solutions of the system involving nonuniform transmission line, the frequency domain results obtained in the previous section are transformed to time domain by the use of FILT shortly described in this section.

D. Computer Implementation

Based on the experiences gained on FILT applied to the transmission lines, proper values are chosen for a, k and p. Satisfactory results are obtained if a is chosen to be between 3 and 5 [2,3,8,9]. p and k (>p) must be chosen sufficiently high to achieve the required accuracy [8,9]; otherwise considerable truncation errors may cause misleading results.

To start the computation of any response of the system in the interval $[\Delta t, t_{\max}]$, specify the above parameters and Δt which is the time difference between the subsequent time intervals at which the response is desired to be known.

In order to compute $f(t_i)$, $t_i=i\Delta t$, $i=1,2,\cdots$;

1) Compute $s_n = (a + j(n-0.5)\pi/t_i'$ for $n = 1,2,\cdots,k+p$,
2) For each uniform line in the system determine the transfer matrix appearing in (2) for each s_n,

3) For each nonuniform line in the system determine the transfer matrix H in (10) as described in Section II.B for each s_n, and calculate output variable (voltage or current) of the system in s-domain,
4) Substituting the s-domain voltages or currents computed in Step 3 in (15) and (14), compute time domain solution at t_i,
5) If $t_i = t_{max}$, set $i=i+1$, goto step 1; otherwise stop.

III. RESULTS AND DISCUSSIONS

The test system shown in Fig. 3 is considered for the application of the proposed method. It is assumed that the tower top is hit by a lightning surge which is characterized by a current $i(t) = 30.397(e^{-t/\tau_1} - e^{-t/\tau_2})$, where $i(t)$ is in kA, t is in μs, τ_1=17.63 μs and τ_2=0.0316 μs; this current is assumed to have a source impedance Z_s= 250 Ω. This waveform represents a 0.2/25 μs impulse with 30 kA peak value. The transmission tower is simulated by an exponential line with characteristic impedance $Z_o = 150e^{qx}$, q=0.00766. It is assumed a propagation constant λ=1/c, where c is the velocity of light. The simple circuit model of the system is shown in Fig. 4, where r_f denotes the footing resistance of the tower. The length of earth wire is 700 m and its mid point is connected to the tower top. It is assumed that both ends of the wire are open and this assumption does not introduce any error to the analysis for the observation time of 0≤t<2τ, where τ is the travel time of the half-line. Since travel time of the tower is much shorter than that of line, this interval is sufficient to determine the response of the tower.

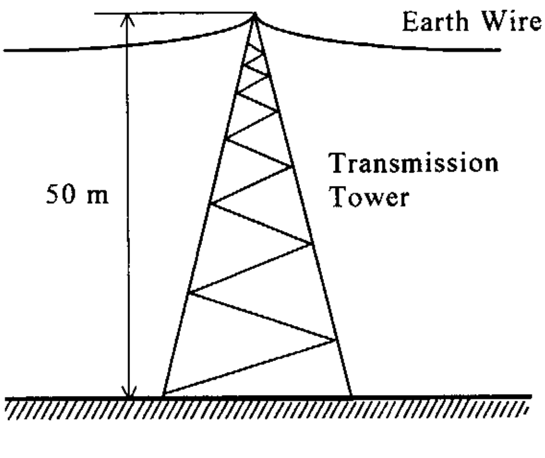

Fig. 3. A high-voltage transmission tower hit by a lightning stroke.

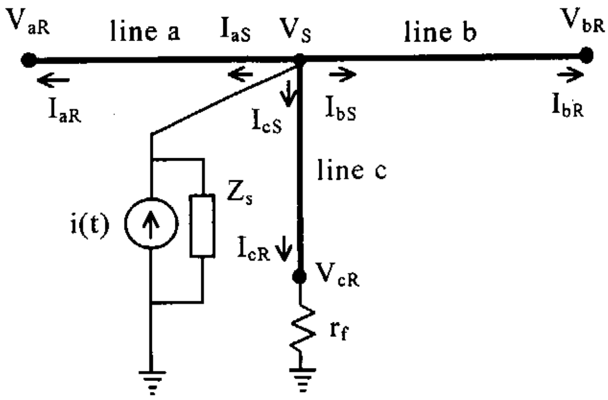

Fig. 4. Equivalent circuit model of the system.

In order to determine the response of the system in s-domain, first, terminal equations of the uniform half-lines (lines a and b) are obtained in the form of (2), and those of nonuniform line c in the form of (10). These equations are written in the matrix form as

$$\begin{bmatrix} V_S \\ I_{aS} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} V_{aR} \\ I_{aR} \end{bmatrix}, \quad (18a)$$

$$\begin{bmatrix} V_S \\ I_{bS} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} V_{bR} \\ I_{bR} \end{bmatrix}, \quad (18b)$$

$$\begin{bmatrix} V_S \\ I_{cS} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} V_{cR} \\ I_{cR} \end{bmatrix}. \quad (18c)$$

Then, the expression for the tower top voltage (V_S) in s-domain is obtained as

$$V_S(s) = I(s)/Y(s), \quad (19)$$

where $I(s)$ is the lightning current and

$$Y(s) = \frac{1}{Z_s} + \frac{a_{21}}{a_{11}} + \frac{b_{21}}{b_{11}} + \frac{r_f c_{21} + c_{22}}{r_f c_{11} + c_{12}}. \quad (20)$$

Mutual effects of the phase conductors are not included into the analysis.

When the time domain response is obtained by using FILT, the results shown in Fig. 5 are obtained; this figure shows voltage waveform at the tower top after the lightning stroke. For the application of the proposed method, the nonuniform line is divided into 10 uniform distributed parameter sections equal in length. The frequency parameters of earth wire are taken into account. Satisfactory results are obtained by FILT with a =5, k=20 and p=10. The effect of the footing resistance of the tower r_f is also shown in the figure. Apparently the peak is not effected by r_f whilst, the reflected waves are much more effected.

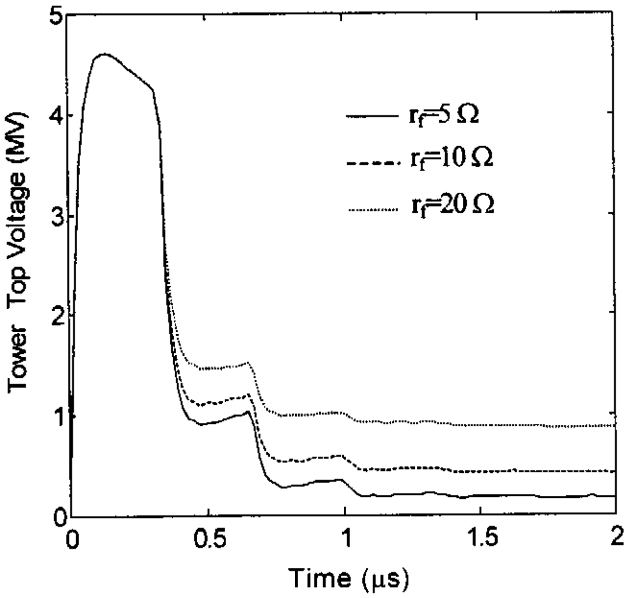

Fig. 5. Transient response of the transmission tower for the sending-end voltage.

IV. CONCLUSIONS

A numerical method suitable for computer programming is presented for the calculation of lightning overvoltages on transmission lines. Nonuniform line is simulated by uniform line sections by dividing it into adequate number of sections. By this way terminal equation describing the system is calculated in s-domain. Since uniform line sections are used to represent the nonuniform line, frequency-dependent parameters and transmission line losses can easily be included in the analysis. Comparing with the other s-domain methods, mathematical formulation and computer implementation of the proposed technique is easy. This method will be further developed to compute lightning overvoltages on phase conductors of a multi-phase transmission system.

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INDUCED OVERVOLTAGE ANALYSIS BY LIGHTNING STROKE NEAR DISTRIBUTION SYSTEM USING TACS-EMTP.

Raúl Montaño   Andrés Hernández   Alberto J. Urdaneta   Javier Rodríguez   Miguel Martínez
Member, IEEE   Senior Member, IEEE

Universidad Simón Bolívar
Caracas-Venezuela. Email: rmonmsal@telcel.net.ve

Abstract. **A methodology for studying overvoltage induced by atmospheric discharges or lightning strokes near electric circuits is presented in this article, based on the model that was developed for that purpose by Chowdhuri-Gross [4]. This tool is based on the EMTP program and in the ease of use provided by the TACS. The results that are presented here belong to the following cases: A model of a conductor in space with distributed parameters without resistance; a model of a conductor in space with distributed parameters with resistance; a conductor in space, with resistance, considering the Kelvin effect, modeled with distributed parameters; a conductor in space, with resistance, considering the variation of the RLC parameters as a function of the frequency; all of which are validated in the literature [1-4, 5-6]. The distance at which the maximum overvoltage is located (also called Critical Overvoltage Distance) was observed at around 4 km. and is affected by the dependence on the frequency of the line parameters.**

Keywords: Transients, lightning, induced overvoltage, TACS-EMTP.

I. INTRODUCTION

Among the phenomena that affect the most the power electrical systems is the overvoltage caused by the atmospheric discharges or lightning strokes.

Historically, more importance has been given to the strokes that hit the circuit directly (either on the phase conductors or on the lineman conductors) than the indirect strokes near the overhead lines. Nevertheless, the importance in considering the strokes that occur near the electrical circuits, has been demonstrated in the literature [1-7, 8].

The EMTP-ATP is the most widely accepted tool for the analysis of the transient electromagnetic phenomenon in electrical systems for the generation, transmission and distribution of power; however, a vacuum exists in the use of EMTP-ATP for the simulation of electrical discharges near overhead lines. In this paper a methodology is proposed that collaborates with the EMTP-ATP system for the simulation of overvoltage induced by strokes near electric circuits.

In the first part of the research, comparative studies were performed that consider distributed parameter models for distribution lines and their concentrated parameter models (Pi circuits). In this case, direct strokes to the lineman cable were evaluated. These discharges are of the (2/75) μsec type with an amplitude of 120kA.

The basic premises of the method used in the work, are[1]:
a.-Only the electrostatic and the magnetic components induced by the return stroke are considered, e.g., the electrostatic effects of the cloud and the stepped leader are neglected.
b.- The charge distribution along the leader stroke is uniform.
c.- The shape of the return stroke current is rectangular. The result with rectangular current wave can be transformed to that with currents of any other waveshape by the convolution integral (Duhamel's theorem.) The computation were extended to current waves having linearly rising front, in order to study the effect of the wavefront of the current on induced voltage wave.
d.- The velocity of the return stroke is constant. It was thought to be of advantage to be able to take the return stroke velocity as a parameter ad to study its effects on the induced voltage.
e.- The lightning stroke is vertical

In the second phase of the research, the TACS-EMTP-ATP tool was formulated in order to be able to study and analyze the dynamic behavior of the overvoltage induced by the strokes in the circuit's perimeter, according to the model developed by Chowdhuri-Gross [5].

After proving the Thevenin and Norton models useful for the current investigation work, different characteristics and phenomenon involved with the modeling of the distribution lines are considered, which represents one of the main enrichments of this work. Mainly, the overvoltage generated in the overhead lines was analyzed considering the effect of the resistance on the conductors and the variation of the electrical parameters as a function of the frequency using the J. Marti model [9].

The proposed technique is based on the use of TACS and of a number of equivalent Thevenin - Norton models, placed in each conductor and separated between each other a certain distance to simulate the electromagnetic lighting of the overhead lines by an electric discharge. The characteristics of the equivalent models are calculated using the procedure proposed by Chowdhuri-Gross[1] for simulating the electromagnetic fields generated by lightning strokes.

The cases that are analyzed here are the following:

- Applying a series of Thevenin and Norton equivalents to a conductor in space, modeled with several concentrated parameter circuits that are cascade connected (also called tandem connection).
- Applying Norton equivalents to a conductor in space without resistance, modeled with several distributed parameter circuits.
- Applying Norton equivalents to a conductor in space, weighing resistance, modeled with a series of circuits with distributed parameters.
- Applying Norton equivalents to a conductor in space, with resistance, considering the Kelvin effect, modeled with several distributed parameter circuits.
- Applying Norton equivalents to a conductor in space, with resistance, considering the variation of the RLC parameters with the frequency.

II. FINDING THE RIGHT CHOWDHURI-GROSS MODEL TO BE APPLIED IN THE EMTP.

As the first approach to the model to be applied, we consider the EMTP's method of simulating the dynamic behavior of the power circuits' passive elements (capacitance and inductors) besides some electric network theorems (see Fig. 1)

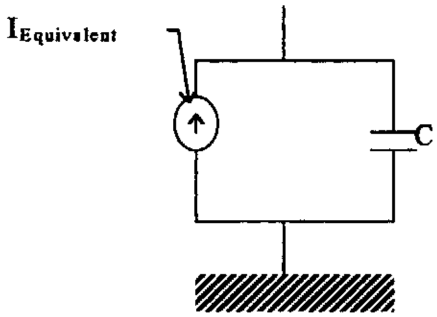

Fig. 1: Approximate model applied to the EMTP.

Where:

$$I_{equivalent} = \frac{2 \cdot C \cdot Vi_{Choudhuri}}{\Delta t} \qquad (1)$$

Where $Vi_{Chodhuri}$, is the solution of equation 3.

When applying the numerical integration methods, we find values that are very close to the time-based function, although keeping a negligible error margin. On the other hand, we can see that the forcing function value depends on the integration rate (Δt) that is assigned. If this value (Δt) is too small, then the resulting function is approximately equal to the voltage (as a function of time) derivative, according to the equivalent proposed in [4].

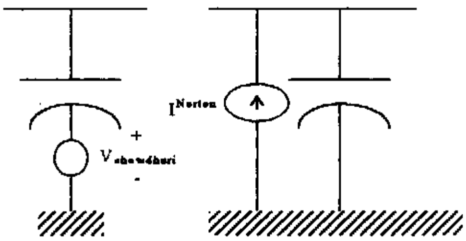

Fig. 2: Thevenin and Norton Chowdhuri-Gross model

This means that:

$$i_{Chowdhuri}^{Norton}(t) = c \cdot \frac{d}{dt} v_{Chowdhuri}^{Thevenin}(t) \qquad (2)$$

When we apply this last equation to the voltage sources of the Thevenin Chowdhuri-Gross equivalent model we obtain:

$$\frac{d}{dt}V_{ij} = \frac{d}{dt}V_{ij1} \cdot \mu\left(t - t_0\right) - \frac{d}{dt}V_{ij2} \cdot \mu\left(t - t_0 - t_f\right) \qquad (3)$$

Where:

$$\frac{d}{dt}V_{ij1} = -\frac{60 \cdot \alpha_1 \cdot h_j}{\beta} \cdot \left(\frac{1-\beta^2}{\beta \cdot c}\right) \cdot \left(\frac{\left(\sqrt{(t-t_0)^2 + a^2} + (t-t_0)\right)}{(t-t_0) \cdot \sqrt{(t-t_0)^2 + a^2} + (t-t_0)^2 + a^2}\right) + \frac{60 \cdot \alpha_1 \cdot h_j}{\beta} \cdot \left(\frac{1}{\sqrt{h_j \cdot c^2 + r_j^2}}\right) \qquad (4)$$

and:

$$\frac{d}{dt}V_{ij2} = -\frac{60 \cdot \alpha_2 \cdot h_j}{\beta} \cdot \left(\frac{1-\beta^2}{\beta \cdot c}\right) \cdot \left(\frac{\left(\sqrt{(t-t_0-t_f)^2 + a^2} + (t-t_0-t_f)\right)}{(t-t_0) \cdot \sqrt{(t-t_0-t_f)^2 + a^2} + (t-t_0-t_f)^2 + a^2}\right) + \frac{60 \cdot \alpha_2 \cdot h_j}{\beta} \cdot \left(\frac{1}{\sqrt{h_j \cdot c^2 + r_j^2}}\right) \qquad (5)$$

III. TACS TOOLS

The EMTP tools that allow the control system analysis under the presence of a transient are called TACS (Transient Analysis of Control Systems). In broad terms, these tools provide the user models that are normally associated with an analogical computer. Besides, these tools not only can be used in the studies for which they were designed, but also allow the user to create signal sources with great ease and freedom, as long as the program's dimensions are considered.

There are different types of sources, that go from step signals, sinusoidal signals, pulse trains (discrete sequence of pulses), slope signals, to free format sources that can be not only of the algebraic type but can also contain logical instructions based on the FORTRAN code.

To work on the induced overvoltage study we need to have access to the definition of the current and voltage sources to be able to apply the right Thevenin and Norton equivalent models. This is why the TACS tools prove to be a reasonable option for applying the model in the EMTP.

There are sources included in the TACS that provide for all these benefits. On the other hand, we needed to specify unitary step sources and to have access to the real integration time, being that required by the Chowdhuri model. These conditions can be found again in this application, since it contains sources that simulate a step with a desirable size and instructions that allow to identify that time.

IV. APPLYING THEVENIN AND NORTON EQUIVALENTS TO A CONDUCTOR IN SPACE, MODELED WITH CONCENTRATED PARAMETERS WITH A CASCADE CONNECTION.

As we know, Chowdhuri and Gross have two models that can applied to the inquiries that were done in this research. The first one is the Thevenin equivalent model, which is easier to apply to a single-phase than to a three-phase case. On the other hand, the Norton equivalent (that can be applied to any case), requires a greater number of computer variables due to the nature of the model.

This is why we need to prove that there is no difference between both models when representing the overvoltage phenomenon. To do this, a 10 kA and 2/75 μsec discharge at a distance of 10 m was considered for a conductor in space with no losses. In both cases, the conductor with Pi circuits with a cascade connection was modeled, therefore extending the study up to a kilometer. The study is not extended a greater distance since we do not intend to determine the maximum overvoltage point in this first test, but to prove that the system response will be the same under these two excitations. Later on, the maximum overvoltage point is determined for this case, considering different phenomena.

The registered overvoltage as a function of time is observed in three points of the conductor; at 0 meters (see curve a), at 500 meters (see curve b) and at 1 km (curve c). For the model with Thevenin equivalents, we obtain the following system response (see Fig. 3).

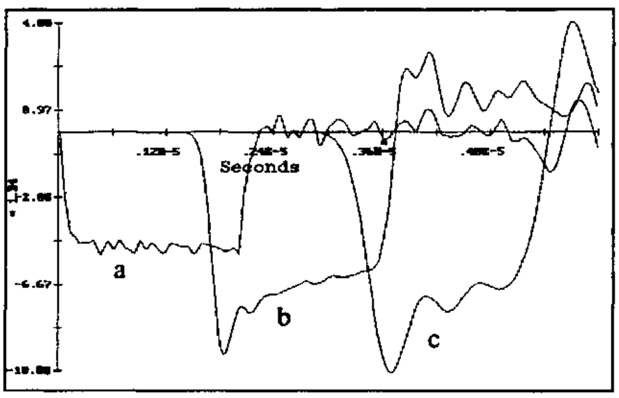

Fig. 3: Overvoltage in different system points for a 2/75 μsec, 10 kA wave. (a) 0 mts, (b) 500 mts, (c) 1 km (Thévenin's model).

While for the model with Norton equivalents, the following response can be observed (Fig. 4):

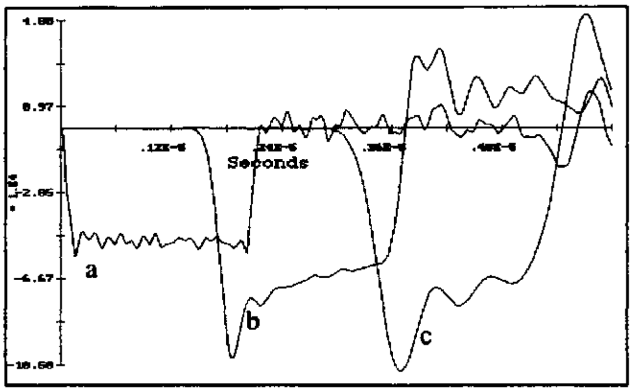

Fig. 4: Overvoltage observed in different points of the system for a 2/75 μsec, 10 kA wave. (a) 0 mts, (b) 500 mts,(c) 1 km (Norton's model).

As we can see, both graphs are very alike when comparing the wave form, size and the frequency in which the peaks appear.

V. APPLYING THE NORTON EQUIVALENT TO A CONDUCTOR LAID IN SPACE, MODELED WITH DISTRIBUTED PARAMETER CIRCUITS THAT ARE CASCADE CONNECTED.

Here we evaluate a wave with the same features, but introducing the following variations in the system:

- All the studies are made with equivalent Norton sources.
- The conductor is modeled with a circuit sequence with distributed parameters that are cascade connected.

The cases that are analyzed here are the following:

a) Overvoltage induced in a conductor without losses.
b) Overvoltage induced in a conductor with losses.
c) Overvoltage induced in a conductor with losses, considering the Kelvin effect.
d) Overvoltage induced in a conductor with parameters that depend on the frequency.

In all of these cases AWG # 2 conductors were used, AAAC, 6201 alloy and the calculation of the conductor's parameters was done with the methodology applied by the EMTP-ATP for calculating overhead line parameters.

a) Overvoltage induced in a conductor without losses.

In this first case, the study is done up to a distance of 7 km, in which it can be noted that the voltage amplifies as the distance from the discharge increases, reaching it's maximum at a distance of 4 km from the discharge (see Fig. 5).

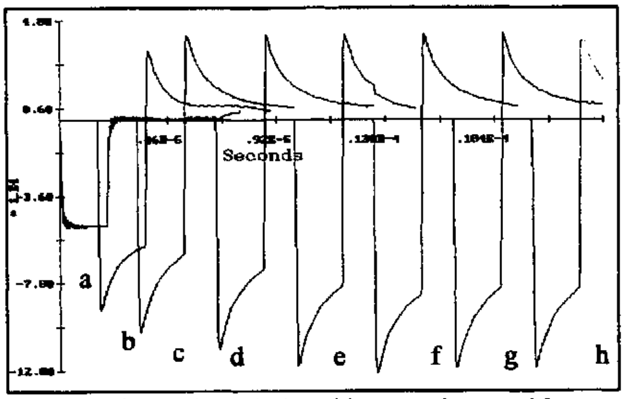

Fig. 5: Overvoltage induced in a conductor without losses. (a) 0mts, (b) 500mts, (c) 1km, (d) 2 km, (e) 3 km, (f) 4 km, (g) 5 km, (h) 6 km.

As we can see in figure 5, after 4 km, the overvoltage peaks turn stable and do not decrease since the conductor model does not have any energy dissipating element. In other words, R = 0 Ω.

b) Overvoltage induced in a conductor with losses.

For this simulation, the conductor resistance is considered at 60 Hz, without giving importance to it's variation as a function of the frequency. It should be noted that this response is similar to the system's real response. According to the study that was done, we can see in the system the following response (Fig. 6):

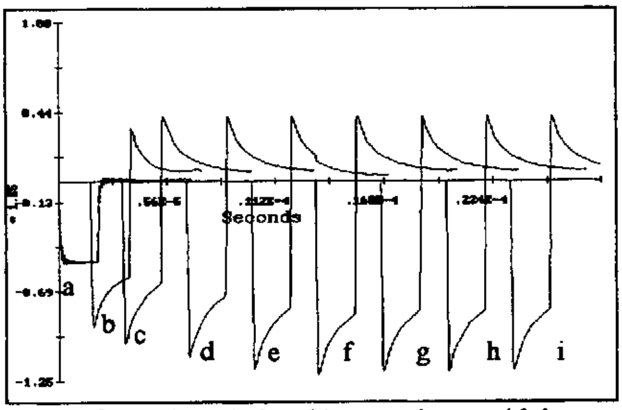

Fig. 6: Overvoltage induced in a conductor with losses. (a) 0mts, (b) 500mts, (c) 1km, (d) 2 km, (e) 3 km, (f) 4 km, (g) 5 km, (h) 6 km, (i) 7 km.

In this case we can see that the distance in which the maximum overvoltage is observed is again 4 km. On the other hand, a decline (although very small - lower than 2%) of the overvoltage peaks can be observed at distances greater than 4 km. This suggests that the overvoltage wave travels to great distances through the conductor. Here we prove that it is correct to neglect the resistance near the discharge point.

c) Overvoltage induced in a conductor with losses, considering the Kelvin effect.

The Kelvin effect was weighed in order to attain a more realistic response for the model. We can see again that the distance from which the maximum overvoltage occurs is 4 km from the closest point to the discharge and it's response can be observed in Fig. 7.

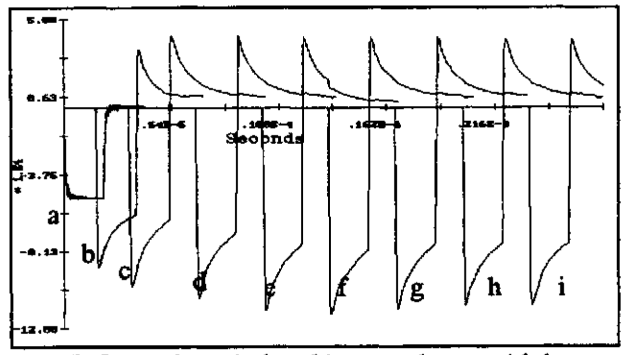

Fig. 7: Overvoltage induced in a conductor with losses, considering the Kelvin effect. (a) 0mts, (b) 500mts, (c) 1km, (d) 2 km, (e) 3 km, (f) 4 km, (g) 5 km, (h) 6 km, (i) 7 km.

In this case, we can see that the maximum overvoltage point is slightly a lesser value than the peaks that were obtained in the previous two cases (around 2% lower) and that when you compare the values after a distance of 4 km, the difference between them is very small.

d) Overvoltage induced on a conductor that is modeled with it's parameters as functions of the frequency.

Since this phenomenon of electromagnetic induction is recognized as involving high frequency and the line parameters (inductance and capacitance) vary with the signal frequency, this last variable should be considered. Therefore, this effect was included in the investigation that was performed. The system response for this case is the one observed in the Fig. 8.

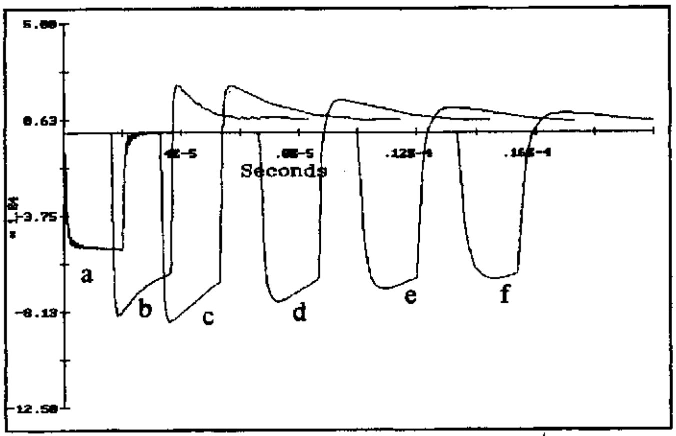

Fig. 8: Overvoltage induced on a conductor considering the dependence of the parameters on the frequency. (a) 0mts, (b) 500mts, (c) 1km, (d) 2 km, (e) 3 km, (f) 4 km.

What makes this case different from the previous cases, is that it can be seen that the maximum overvoltage occurs at a distance of 1 km from the discharge point. The highest peak is approximately 30% lower than the peaks from the previous cases. We also see that the peaks that follow decrease more than before (approximately 25% of the highest value). After observing this, we predict that the distance that this wave can travel is much shorter than in the previous cases.

VI. CONCLUSIONS

- There is a distance parallel to the conductor that reaches from the closest point on the line to the stroke incidence to the point in which the maximum overvoltage takes place when lightning strikes. This can be called Critical Overvoltage Distance. After performing certain simulations, it was determined that this distance is around four kilometers, when the line parameter's dependence on the frequency is not considered and one kilometer when this effect is contemplated.

- The subjection of the line parameters to the frequency affects to a considerable degree the voltage values and the distance in which the worst (maximum) overvoltage is found.

- Weighing the conductor resistance for this study wasn't an important element in the results that were attained, so considering the resistance negligible is a good approximation.

- The methodology that was proposed, along with the computing tool that was applied are effective for the analysis of the overvoltage induced by lightning strokes near the distribution circuits.

VII. TERMINOLOGY

- I_0: Step function amplitude
- β: Relation between the return stroke and the speed of light in vacuum.
- h_j: Distance or height between the conductor and the ground $r_j^2 = x^2 + y_{0j}^2$.
- x: Distance between the observation point on the line and the closest point to the discharge incidence.
- y_{0j} : Perpendicular distance from the conductor to the stroke's incidence point.
- t_0: Travel time of the striking discharge.
- $u(t-t_0)$: Step function that is centered in t_0.
- t_f : Discharge augmenting time.
- t_h : Time that it takes to reach one half of the peak value of the discharge signal.
- h_C: Height of the cloud.

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