ASPECTS CONCERNING THE ANALYSIS OF GROUNDING SYSTEMS' TRANSIENT BEHAVIOUR USING EMTP

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INTRODUCTION

Grounding grids are important elements of electric networks with the task to create a reference potential for a group of electric and electronic apparatus and to disperse fault currents into the earth. In contrast to their DC and permanent behaviour the transient one was less studied in the world due to its complexity.

It is important to know the transient response of a grounding system for studying the lightning stroke effects on electrical installations (especially when the grounding grid is large and thus propagation phenomena on it cannot be neglected).

There are two main groups of approaches available in theory, to modelise and study the buried conductors of a grounding grid:

- ***The Electromagnetic Field Approach*** is the most rigorous one, making the fewest approximations possible regarding the theorems of Electromagnetism. However the computational effort is very important. Among others, Grcev and Dawalibi use this approach [1].
- The ***Circuit Approach*** attempts the representation of some actual parts of the studied configuration by means of electrical circuit elements. If these elements are lumped then the approach (also called "Network" representation) is the least complex but it cannot reasonably deal with frequency dependencies and propagation phenomena. The "Transmission Line" (TL) representation, where primary electric elements are distributed, is better suited for such situations (and this is the case for large grounding systems).

Since the accurate measurement of the electrical parameters of the earth is not a simple task, any of the two approaches to modelisation will have a limited precision.

Some limitations of the Circuit Approach arise from the difficulty to derive general analytical formulas for the electrical parameters of the equivalent transmission line model. These formulas are, usually, only approximations of the exact integral form of solution. Furthermore, it is difficult to deal with the inhomogeneity of earth (only a detailed EM Field approach could handle this).

Even if the Circuit approach cannot be as accurate as the Electromagnetic Field one, it offers a flexible way to integrate the model of the grounding grid with the neighbouring connected network (allowing thus the study of the whole). Furthermore, the computational effort is smaller.

BRIEF DESCRIPTION OF THE USED METHOD

The work presented in this paper is based on the Circuit approach, using the Transmission Line representation. The grounding grid to be analysed is decomposed in elementary straight segments modelled as transmission lines with frequency dependent parameters. Analytical formulas and primary proposals for algorithms to compute the corresponding parameters of such a model for buried conductors were made available by Sunde in [2], where results are presented of investigations by him and others.

This model is than interfaced with MicroTran[3] v2.04, a personal computer version of the ElectroMagnetic Transients Program (EMTP) family. This is a ***time-domain*** simulation program and for all the implemented TL models it employs the ***travelling wave*** technique, pioneered by Bergeron.

There were several techniques expected to incorporate into EMTP the frequency dependency of the transmission line model parameters. The only technique actually implemented in MicroTran v2.04 is that proposed by J. Marti [3] for aerial lines. Because EMTP computes the solution for a multi-conductor transmission line in the modal domain, the J.Marti model considers the modal transformation matrix to be constant in frequency, which is not the general case, especially for buried equipments as cables and grounding grids. However, for a single conductor, this limitation does not arise. Menter employed the J.Marti model for the case of buried conductors[4]. The present paper contains proposals for improvements of this technique in order to maximize both the accuracy and the domain of validity. They will refer to the analytical formulas for the equivalent transmission line model, to the method for integration into the J.Marti model, but also to a way to process the results of an EMTP simulation in view of their interpretation.

The advantage of the connection with the EMTP family lies in its versatility (since various cofigurations of grounding grids may be easily prepared for simulation) and in the opportunity to analyse at once both aerial and buried parts of the network.

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[3] MicroTran® is a registered trademark of Microtran Power System Analysis Corporation from Vancouver, Canada.

Due to the need to pre- and post-process data exchanged with MicroTran the authors conceived a Visual Interface for MicroTran that contains:

- the Graphical Circuit Editor that let the user to visually design the electric scheme and keeps track of its topology, generating automatically the corresponding input data files for MicroTran;
- the Buried Conductor Pre-processor computes the corresponding transmission line parameters for the J.Marti model;
- the Matlab Postprocessor has been used to compute the current and voltage distributions along each conductor segment, the boundary values being given by MicroTran;
- interfaces with plotting programs like MT Plot that comes with MicroTran.

The current and potential distributions obtained may serve for preliminary conclusions about the behaviour of the grid and to the computation of the field produced in the transient process in the neighbouring volume.

In the next sections, only some original contributions to this technique will be emphasised and argued with simulation results.

TRANSMISSION LINE APPROACH FOR BURIED CONDUCTORS

Let us consider the configuration in Figure 1, where a cylindrical long conductor (extending from z=0 in the positive direction) is buried horizontally in direct contact with a semi-infinite homogeneous medium (the earth), where index 1 is used in connection with the air and index 2 for the earth.

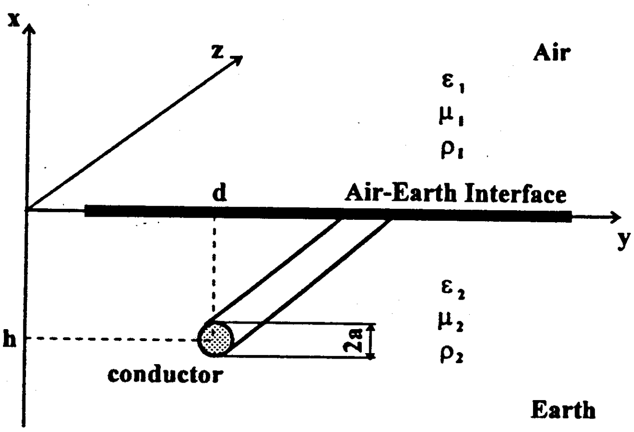


Figure 1 Horizontally buried conductor.

The well-known transmission line equations that usually apply for two parallel long conductors surrounded by an infinite, isotropic medium still apply for one single long conductor with the same conditions as for the two conductors' configuration. In the later case the current will return through the surrounding medium and the equivalent parameters of the transmission line model will be influenced by this geometry.

$$\frac{d\underline{I}}{dz} = -\underline{Y}'\underline{V}; \qquad \frac{d\underline{V}}{dz} = -\underline{Z}'\underline{I} \text{ or}$$

$$\frac{d^2\underline{I}}{dz^2} = \underline{\gamma}^{2}\cdot\underline{I}; \qquad \frac{d^2\underline{V}}{dz^2} = \underline{\gamma}^{2}\cdot\underline{V} \qquad (1)$$

with

$$\underline{Z}' = R'(\omega) + j\omega\cdot L'(\omega);$$
$$\underline{Y}' = G'(\omega) + j\omega\cdot C'(\omega)$$

where $\underline{Z}'$ is the unit length longitudinal impedance, $\underline{Y}'$ is the unit length transversal admittance and R', L', G', C' are the primary longitudinal and transversal distributed electrical parameters that may all be functions of frequency.

$\underline{Z}'$ and $\underline{Y}'$ may be written as

$$\underline{Z}' = \underline{Z}'_i + \underline{Z}'_e; \qquad \underline{Y}'^{-1} = \underline{Y}'^{-1}_i + \underline{Y}'^{-1}_e \qquad (2)$$

where terms indexed with "i" (from "internal") show the contribution of the actual conductor while those indexed with "e" (from "external") show the contribution of the current return through the medium.

The secondary parameters are defined as:

$\underline{\gamma} = \sqrt{\underline{Z}'\cdot\underline{Y}'}$ the propagation parameter;

$\underline{Zc} = \sqrt{\dfrac{\underline{Z}'}{\underline{Y}'}}$ the characteristic impedance (3)

and the solution of Eq.1 may be expressed using them, in an exponential form:

$$\underline{I}(z) = A\cdot e^{-\underline{\gamma}\cdot z} - B\cdot e^{\underline{\gamma}\cdot z};$$

$$\underline{V}(z) = \underline{Zc}\cdot\left(A\cdot e^{-\underline{\gamma}\cdot z} + B\cdot e^{\underline{\gamma}\cdot z}\right); \qquad (4)$$

with A and B integration constants, which depend on boundary and initial conditions.

When analysing the general integral solution for the electric field of such a configuration (that may be found elsewhere, e.g. in [5]), when the current is supposed to propagate exponentially as $\underline{I}\cdot e^{-\underline{\gamma}\cdot z}$, the authors sythetised the contributions of the earth to the unit length longitudinal impedance $\underline{Z}'$ and transversal admittance $\underline{Y}'$ of the equivalent transmission line in the following general formulas:

$$\underline{Z}'_e = \frac{j\omega\cdot\mu_0}{2\pi}\cdot\left[K_0\left(\chi_2\cdot R\right) - K_0\left(\chi_2\cdot R'\right) + \right.$$
$$\left. + \int_{-\infty}^{+\infty}\frac{e^{u_2\cdot(x+h)}}{u_1+u_2}\cdot e^{-j\cdot\lambda\cdot(y-d)}\cdot d\lambda\right]; \qquad (5)$$

$$\underline{Y}'^{-1}_e \cong \frac{1}{2\pi\cdot\left(\sigma_2 + j\omega\cdot\varepsilon_2\right)}\cdot\left[K_0\left(\chi_2\cdot R\right) + K_0\left(\chi_2\cdot R'\right)\right]$$

where K_0 is the modified Bessel function of the second kind and order 0 and the following notations apply:

$j = \sqrt{-1}$

$\omega = 2 \cdot \pi \cdot f$, *the angular frequency,*

ε = *electrical permitivity,*

μ = *magnetic permeability,*

γ = *actual propagation parameter,*

ρ = *resistivity,* $\quad \sigma = 1/\rho$ = *conductivity,*

$$k_m^2 \stackrel{\Delta}{=} -j\omega \cdot \mu_m \cdot \left(\sigma_m + j\omega \cdot \varepsilon_m\right)$$

= int *rinsic wave number of the medium m,*

$$\chi_m^2 = -k_m^2 - \gamma^2, \qquad \text{with} \quad \mathrm{Re}\{\chi_m\} > 0;$$

$$u_m^2 \stackrel{\Delta}{=} \chi_m^2 + \lambda^2, \qquad \text{with} \quad \mathrm{Re}\{u_m\} > 0;$$

$$R = \sqrt{(x-h)^2 + (y-d)^2} = a;$$

$$R' = \sqrt{(x+h)^2 + (y-d)^2} = \sqrt{4 \cdot h^2 + a^2};$$

Note that this configuration implies that h<0 and for the field in the earth x<0.

The integral term that lasts in $\underline{Z}'_e$ formula is difficult to evaluate for an arbitrary deep value h. Nevertheless it should be noticed that:

- for a conductor at the surface of the earth (h=0) $\underline{Z}'_e$ is given only by this term and may be evaluated as:

$$\underline{Z}'_e \cong \frac{-j\omega \cdot \mu_0}{\pi \cdot k_2^2 \cdot a} \cdot \left[j\gamma \cdot K_1(j\gamma \cdot a) - \chi_2 \cdot K_1(\chi_2 \cdot a)\right]; \qquad (6)$$

with K_1 the modified Bessel function of second kind and first order and a conductor's radius;

- if the conductor is buried at high depth this term will vanish and the propagation parameter approaches the intrinsic wave number of the earth.

These remarks suggest formula *(6)* as an estimate for the discussed integral term with radius a replaced by $\sqrt{a^2+4 \cdot h^2}$ in the range of depth usually encountered. Sunde proved in [2] that for frequencies high enough to allow neglection of $\underline{Z}'_i$ with respect to $\underline{Z}'_e$, the propagation parameter for a conductor at the air-earth interface will approach $\gamma \cong k_2/\sqrt{2}$. For low frequencies, however, conductor's contribution is dominant and $\underline{Z}'$ will approach the DC value whilst $|\gamma|$ becomes constant with the frequency. The above suggested formulas *(5-6)* fulfill reasonably all these specifications.

Figure 2 shows the evolution of the propagation parameter's modulus in a wide frequency range for two extreme values for the depth h. This result conforms to the above discution (values for great depth are about 40% higher than those obtained for conductor near the surface).

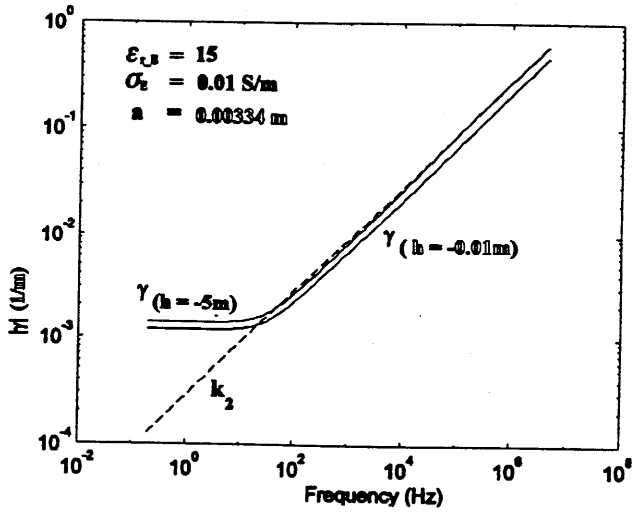


Figure 2 $|\gamma|$ for different depths.

These values for γ result when solving first equation of *(3)* which is now transcendendal since $\underline{Z}'$ and $\underline{Y}'$ are functions of γ.

As a remark, when the arguments of modified Bessel functions K_0 and K_1 have their modulus smaller then 0.01, than it is permissible to approximate them as

$$K_0(u) = \ln\left(\frac{1.1229}{u}\right); \qquad K_1(u) = \frac{1}{u} + \frac{u}{2} \cdot \ln\left(\frac{1.851}{u}\right)$$

and the earth contributions become:

$$\underline{Z}'_e \cong \frac{j\omega \cdot \mu_0}{2\pi} \cdot \left[\ln\left(\frac{1.851}{\chi_2 \cdot a}\right) + \frac{\gamma^2}{k_2^2} \ln\left(\frac{j\gamma}{\chi_2}\right)\right]; \qquad (7)$$

$$\underline{Y}'^{-1}_e \cong \frac{1}{\pi \cdot \left(\sigma_2 + j\omega \cdot \varepsilon_2\right)} \cdot \ln\left(\frac{1.1229}{\chi_2 \cdot \sqrt{2ah}}\right);$$

This hypothesis, however, is not true for the whole range of frequencies and combinations of earth parameters from the real life. For example, when h=0.5m, soil conductivity σ_E=0.1S/m and relative permeability ε_{rE}= 20 and the copper made cunductor has a 10mm diameter, then $|\chi_2 R'|$ reachs the unity at 1MHz. In order to have unique formulas, reliable and general, the authors allways used equations *(5-6)*.

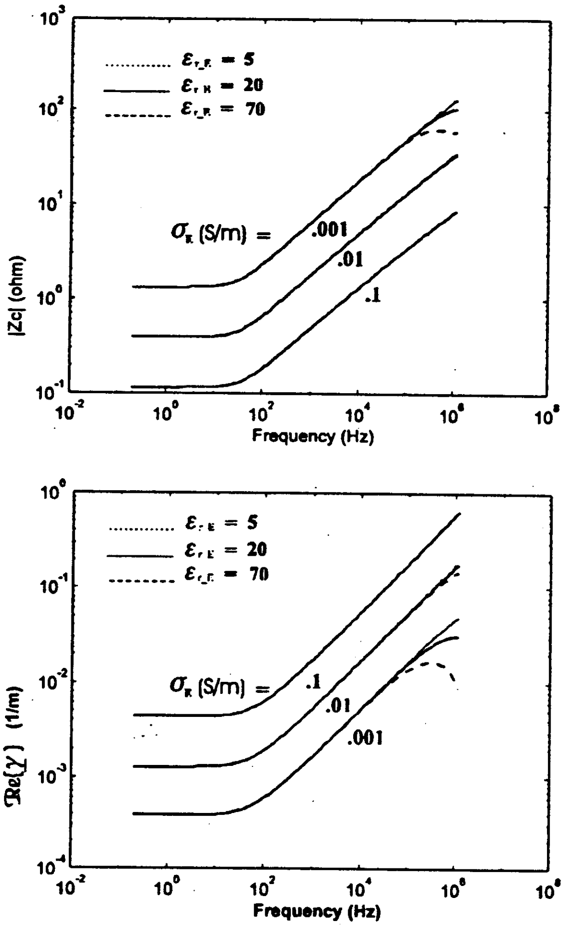
For a cylindrical non-insulated conductor the internal contributions are:

$$\underline{Z}'_i = \frac{j\underline{\gamma}_i \cdot \rho_c}{2\pi \cdot a} \cdot \frac{J_0\left(j\underline{\gamma}_i \cdot a\right)}{J_1\left(j\underline{\gamma}_i \cdot a\right)} = \frac{j\underline{\gamma} \cdot \rho_c}{2\pi \cdot a} \cdot \qquad (8)$$

$$\cdot \frac{ber_0\left(\left|\underline{\gamma}_i\right| \cdot a\right) + j \cdot bei_0\left(\left|\underline{\gamma}_i\right| \cdot a\right)}{ber_1\left(\left|\underline{\gamma}_i\right| \cdot a\right) + j \cdot bei_1\left(\left|\underline{\gamma}_i\right| \cdot a\right)}; \qquad \underline{\gamma}_i = \sqrt{\frac{j\omega \cdot \mu_c}{\rho_c}}$$

$$\underline{Y}'^{-1}_i = 0 \qquad (non\ insulated\ coductor);$$

$\rho_c, \mu_c =$ *coductor's resistivity and permeability*;
where J0 and J1 are Bessel functions of first kind for complex arguments and ber and bei are Kelvin functions of respective orders. The internal impedance per unit length is influenced by the skin effect and is frequency dependent.



(a)

(b)

Figure 3. |$\underline{Zc}$| (a) and Re{$\underline{\gamma}$}(b) as functions of frequency and earth properties.

The secondary parameters suffice for the description of a conductor as transmission line. They are complex valued, frequency dependent and should be computed for the whole range of frequencies that may occur in the spectrum of the exciting signal. For lightning studies the minimum frequency range to be taken into account is 0...1MHz [6].In figure 3 the frequency dependency of the secondary parameters is shown by means of a parametric analysis. They were drawn for a cylindrical copper conductor of 7mm diameter horizontally buried at 0.5m under the surface of the ground.

The conductivity of the earth has a major importance in the whole frequency range while its capacitance is important only for low conductive earth and at frequencies above 100kHz.

INTERFACING WITH THE J. MARTI MODEL OF MICROTRAN

For the computation to be fast J.Marti transmission line model use recursive convolution to dynamically solve Eq (1) in the time domain. The recursive convolution becomes efficient when the complex valued characteristic impedance $\underline{Zc}(\omega)$ and propagation function $\underline{A}(\omega) = e^{-\underline{\gamma}(\omega)*l}$ are expressed as rational functions. It is then necessary to identify their zeros and poles. In his original pre-processor for aerial lines Marti use Bode's asymptotic fitting method for the modulus of each of the two functions analytically calculated. For the special case of buried single conductors the algorithm employed by the authors is similar. The analytically computed modulus is represented in a log-log chart as a function of frequency. A variable width tolerance band around the modulus function is imposed by a modified relative error criterion. The searching procedure starts from the smallest frequency with a null slope and each time the asymptotic tracing violates the tolerance strip there is a zero or a pole added to the rational approximating function and the slope is modified correspondingly (increased with 20dB for a zero and decreased for a pole). Next a Newton-type optimising procedure try to further minimise the modulus relative error between the rational approximation and the analytically computed values.

The fitting method pais attention only to the modulus of the complex functions. The phase error, defined as $\Delta\varphi = \varphi_{aprox} - \varphi_{orig}$, has to be verified and corrected when possible. Because the original function to be fitted is computed with approximating formulas the nature of the phase error is uncertain. This error may arise from imprecisions in the fitting process as well as from imprecisions in the computation of the original function. Only in the former case (that is if the values obtained for the original function may be trusted) an attempt should be done to correct this phase error. The fitting method requires that this correction be done with a real zero-pole pair. When this correction is desired the following relation stands:

$$-\Delta\varphi = \arg\left\{\frac{s - p_{corr}}{s + p_{corr}}\right\} = -2 \cdot atn\left(\frac{\omega}{p_{corr}}\right);$$

with $s = j\omega$ the Laplace operator,
$p_{corr} > 0$ from the stability condition.

Since $\omega > 0$ it can be seen that only $\Delta\varphi > 0$ may be corrected by this method. When this applies the value of p_{corr} results from $p_{corr} = \dfrac{\omega}{tn\left(\dfrac{\Delta\varphi}{2}\right)}$.

Thus, phase correction of this kind is recommended in a limited set of situations and should be employed with caution.

Finally the residues and poles of the rational approximations are written down in a special file that will be read in by the EMTP kernel at simulation time. The input file, that contains topological and simulation information for MicroTran, is automatically generated by the Visual Interface.

COMPUTING THE CURRENT AND POTENTIAL DISTRIBUTION ALONG EACH CONDUCTOR SEGMENT

As it has been told in the brief initial description the grid to be analysed should be decomposed into "elementary" straight segments. The "elementary" segment is the biggest piece of conductor with connections only at two ends and that may still be regarded as "straight" between these two ends. The post-processor described bellow allow finding the values for current and potential at any point along the segment.

MicroTran produces as output data after each simulation the currents and potentials at the ends of each conductor segment as functions of time. The post-processor, created in MATLAB, Fourier transforms this functions from the time to the frequency domain. Then Eq (3) is employed to compute the current and potential distribution along the conductor as functions of frequency. To obtain these distributions in the time domain the results are Inverse Fourier transformed.

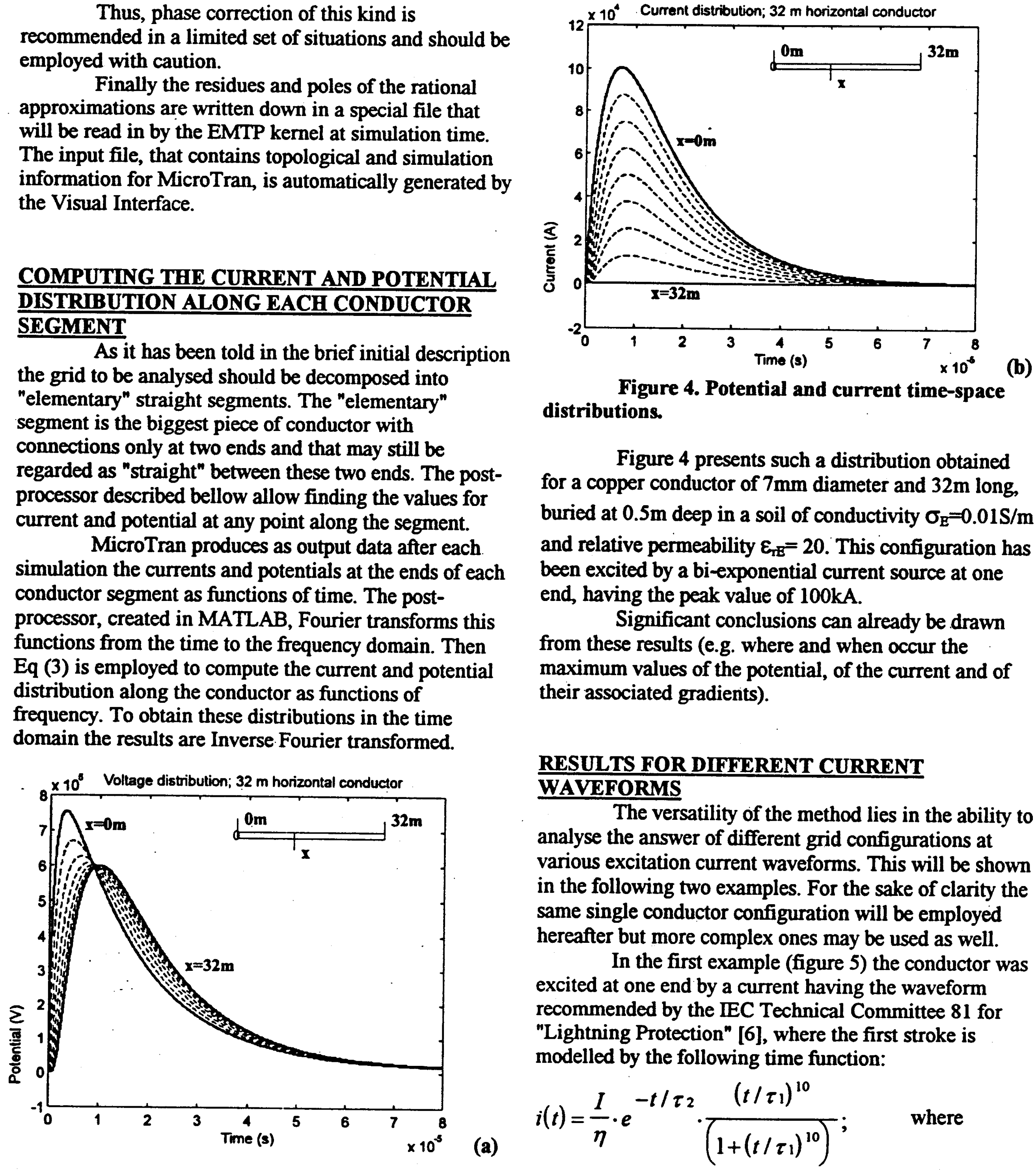


Figure 4. Potential and current time-space distributions.

Figure 4 presents such a distribution obtained for a copper conductor of 7mm diameter and 32m long, buried at 0.5m deep in a soil of conductivity σ_E=0.01S/m and relative permeability ε_{rE}= 20. This configuration has been excited by a bi-exponential current source at one end, having the peak value of 100kA.

Significant conclusions can already be drawn from these results (e.g. where and when occur the maximum values of the potential, of the current and of their associated gradients).

RESULTS FOR DIFFERENT CURRENT WAVEFORMS

The versatility of the method lies in the ability to analyse the answer of different grid configurations at various excitation current waveforms. This will be shown in the following two examples. For the sake of clarity the same single conductor configuration will be employed hereafter but more complex ones may be used as well.

In the first example (figure 5) the conductor was excited at one end by a current having the waveform recommended by the IEC Technical Committee 81 for "Lightning Protection" [6], where the first stroke is modelled by the following time function:

$$i(t) = \frac{I}{\eta} \cdot e^{-t/\tau_2} \cdot \frac{(t/\tau_1)^{10}}{\left(1+(t/\tau_1)^{10}\right)}; \qquad \text{where}$$

I = peak current; t = time;
η = correction factor for the peak current;
τ_1 = front time constant; τ_2 = tail time constant.

The derivative at origin is nil as in real life situations.

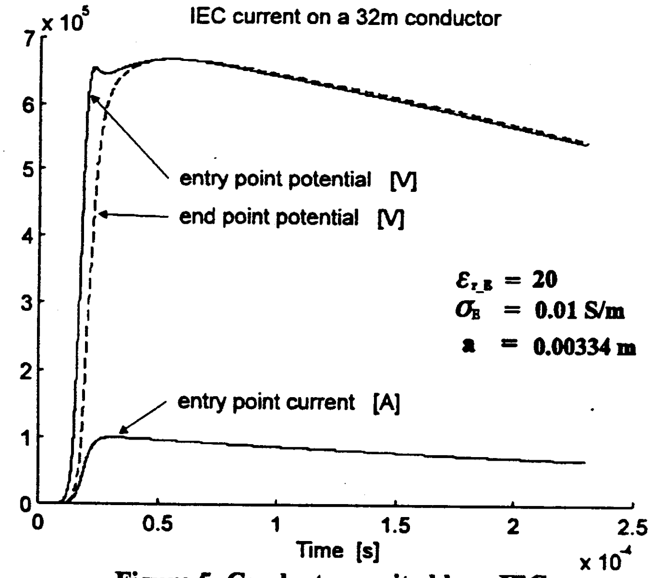


Figure 5. Conductor excited by a IEC recommended current waveform.

The second example (figure 6) shows results of simulation on the same configuration excited by one of the recorded lightning current waveforms [7], grabed and digitized by means of an image processing technique for video camera shots [8].

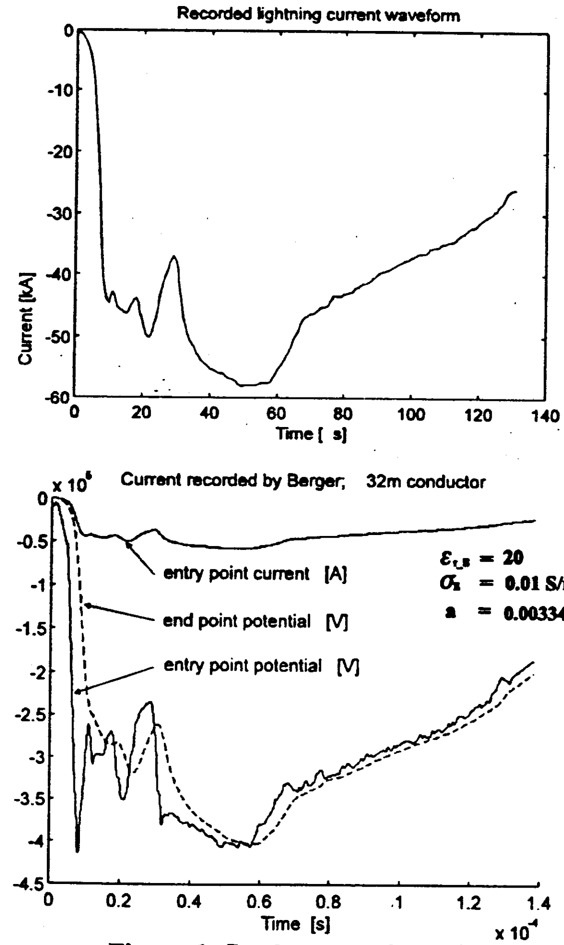


Figure 6. Conductor excited with the current waveform recorded by Berger.

For both types of above discussed excitation signals their frequency spectrum vanishes about 1MHz.

CONCLUSIONS

The goal of the presented work was to find a practical and accessible tool for analysing the transient performance of grounding grids. Using the MicroTran version of the EMTP family and pre- and post-processing routines created by themselves, the authors obtain the current and potential distributions along the conductors of one grid excited by lightning current pulses. These may serve as input data in the calculus of the electromagnetic field generated by the grid.

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REFERENCES

[1] L. Grcev, F. Dawalibi, "An electromagnetic model for transients in grounding systems", IEEE Transactions on Power Delivery, Vol.5, No.4, 1990.

[2] E.D. Sunde, "Earth conduction effects in transmission systems", 2nd edition, New York, Dover Publications, 1968.

[3] J.R. Marti, "Accurate modelling of frequency-dependent transmission lines in electromagnetic transients simulations", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No.1, pp. 147-155, January 1982.

[4] F.E.Menter, "Computation of electromagnetic transients in extended grounding systems" (in German), Ph.D. thesis, Technical University of Aachen, Aachen: Shaker 1993.

[5] Directives CCITT (Comité Consultatif International Télégraphique et Téléphonique) (concernant la protection des lignes de télécommunication contre les effets préjudiciables des lignes électriques et des chemins de fer électrifiés), Vol III, "Couplage capacitif, inductif et conductif: théorie physique et méthodes de calcul", Union Intenationale des Télécomunications, Genève 1989.

[6] Recommendations of IEC Technical Committee 81 "Lightning Protection" based on the Standard CEI/IEC 1024-1.

[7] K.Berger, "Wissenschaftlicher Bericht ùber die Blitzforshung auf dem San Salvatore im den Jahren 1963...1971".

[8] I.Baran, "Review of lightning current parameters", CIGRE Report WG 33.01.03 (Lightning Interception), Paris, September 1994.