

SOFTWARE MODUL DESIGNED FOR THE ANALYSIS OF THE LIGHTNING PROPAGATION ON OVERHEAD LINES

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REZUMAT. Lucrarea abordează domeniul modelării numerice a perturbațiilor electromagnetice pe linii de înalta tensiune. Propagarea perturbațiilor pe linii de înalta tensiune presupune utilizarea modelului prin linii electrice lungi. În această lucrare este prezentat principiul modelării liniilor electrice prin linii lungi neuniforme, modul de calcul a parametrilor lineici, iar apoi se prezintă algoritmul de calcul numeric implementat, respectiv aplicații numerice utilizând diferite impulsuri standard aplicate unui tronson LEA. Este accentuat impactul prezentei solului conductiv în determinarea parametrilor.

Cuvinte cheie: perturbații atmosferice, metoda liniilor de transmisie, trazeț.

ABSTRACT. The paper approaches the topic of the numerical modelling of the electromagnetic disturbances on HV lines. The disturbances propagation requires that the transmission lines model to be taken into consideration. In this paper, the principles of modelling using non-uniform transmission lines, the per-unit-length parameters computation, and then the numerical computation algorithm implemented and several examples using a concrete HV line to which several standard test signals are presented. It emphasized the impact of the soil conductivity in determining this parameters.

Key words: atmospheric perturbations, transmission lines method, lightning.

1. INTRODUCTION

The paper proposes a numerical computation module designed for the analysis of the atmospheric perturbations on the high voltage (HV) lines. Because we deal with high – frequency electromagnetic pulses, the HV line parameters are modelled using the Transmission Line Method (TLM). The computation module implemented requires as input data all geometrical particularities of the HV line under study and computes the per-unit-length parameters of the line taking into account the Carson's theory. Imperfect ground present is included in model. In this case imperfect ground is modeled as return path. The computation module allows the geometrically necessary

exact data insertion and the determination of the line parameters. In addition will be presented some concrete practical example which allows the realisation of a comparative study of the influence implemented models on the imperfect ground (real).

2. THEORETICAL BACKGROUND

The principle of modelling the non-uniform transmission lines is based on the idea of dividing the line into multiple pieces of uniform lines with the length very small in comparison with the wavelength. A suggestive representation is shown in Fig. 1.

Thus, the non-uniform line is modelled by a sequence of series quadripoles as suggested in Fig. 2.

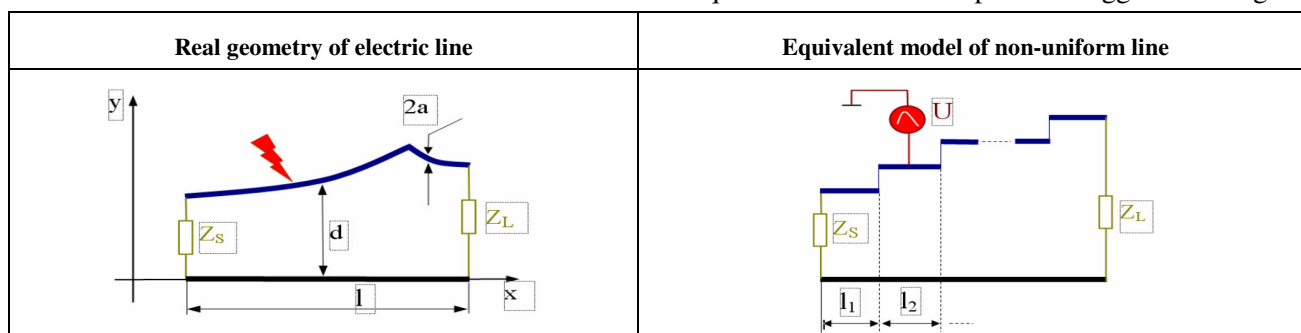


Fig. 1. Modelling using non-uniform transmission lines.

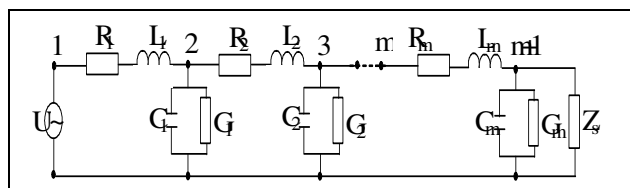


Fig. 2. The equivalent circuit for a non-uniform line composed by series quadripolar cells

The constituent elements of the quadripolar cells will be computed taking into account the line geometrical particularities. The numerical values of the circuit elements are computed for each cell of the discretization taking into account the relief and implementation particularities of the HV line under study.

In this light, the numerical modelling of the electromagnetic disturbances propagation on HV lines can be achieved using well-known professional software packages designed for circuits' numerical analysis. In this paper the PSPICE software that is included in the ORCAD 9.2 package was used.

A line termination is needed at each side of the line to prevent reflection that could affect the simulated overvoltages.

Tower models employ the linear segmented model in which the surge impedance of tower is calculated with Sargent expression:

$$Z_T = 60 \left[\ln \sqrt{2} \left(\frac{2h}{r} \right) - 1 \right] \quad (1)$$

where h is the height of the calculated part of tower (m) and r is the equivalent radius of the part of tower (m).

It is composed of four sections that represent the tower sections between cross-arms. Each section consists of a lossless line in series with a parallel R-L circuit, included for attenuation of the traveling waves. Parallel circuit components were calculated with the following formulas:

$$R_i = \frac{2Z_{Ti} \ln \sqrt{\gamma}}{h_1 + h_2 + h_3} h_i \quad (2)$$

$$L_i = \alpha R_i \frac{2H}{V_i} \quad (3)$$

where α is damping coefficient, γ is attenuation coefficient, V_i is surge propagation velocity and H is overall height of the tower.

Line surge arresters parallel to the phase insulators of the line prevent back-flashovers at all towers. Arrester model used in this paper is that proposed by the working group 3.4.11 of IEEE which is the frequency-dependent model. For this model the non-linear V-I characteristic is represented with two section of nonlinear resistance designated A_0 and A_1 . The two

section are separated by a R-L filter and some formulas are given in [6] to calculate the parameters.

Line's insulators chains are modeled by a capacitors network and the electrical properties of porcelain.

The lightning stroke is represented as a voltage source [7]. Fig. 3 shows the concave waveform chosen in this work:

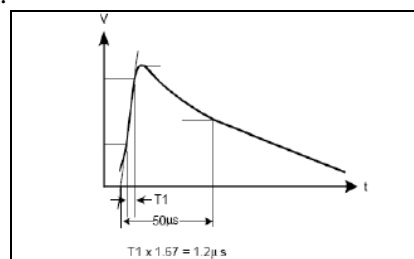


Fig. 3. IEC 61000-4-5 Voltage impulse

3. THE COMPUTATION MODULE IMPLEMENTED

The general flowchart of the numerical algorithm implemented in accordance with the details outlined in the above paragraphs is presented in Fig. 4.

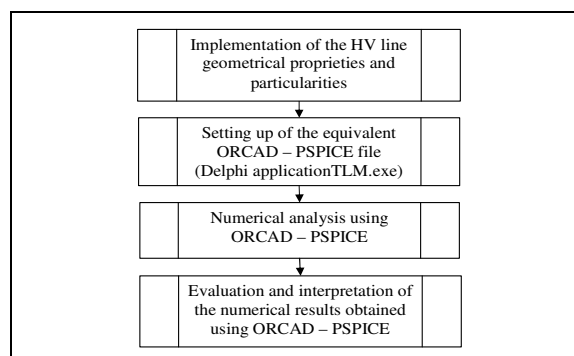


Fig. 4. General flowchart structure of the numerical analysis algorithm implemented

The module responsible for the numerical implementation of the HV line geometrical properties was implemented as a DELPHI application. The outcome of this module is a PSPICE-compatible file. Thus, this module acts as an interface between the problem to be solved and the software package that performs the actual numerical computations presented as a flowchart in Fig. 5.

The constitutive elements of this module are: description of the HV line geometry, the computation of the quadripolar cell geometrical coordinates taking into account the HV line spans, the per-unit-length parameter computation for each quadripolar cell, the perturbation sources configuration after which results the generation Pspice file.

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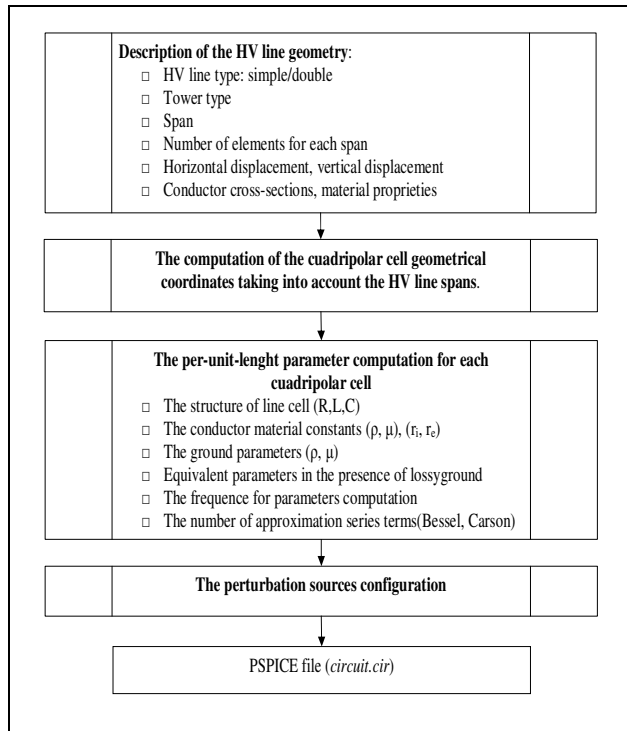


Fig.5. The flow chart of the module interfacing the HV line properties with its equivalent PSPICE file

4. PER-UNIT-LENGTH PARAMETERS OF LINE

The external parameters (self inductance of conductor, mutual inductance of conductor) in the presence of losses ground will be done in assumption of the depending by frequency of earth return path. In fact both self and mutual impedances are influenced by the earth return current. The method which is implemented for calculation of parameters is the well known Carson's method [12].

Self Impedance includes three components: the reactance of the loop inductance L_{ii} assuming that the line (overhead line) and the earth are perfect conductors, the internal impedance of line Z_c and the ground impedance Z_g . In these conditions the conductor's impedance can be written:

$$Z_{ii} = j\omega L_{ii} + Z_c + Z_g \quad (4)$$

The loop inductance is:

$$L_{ii} = \frac{\mu_0}{2\pi} \ln \frac{2h_i}{r_i} \quad (5)$$

in which $\mu_0=4\pi \cdot 10^{-7}$ H/m is the permeability, r_i the radius of the conductors and h_i the height of the

conductor above the ground. The internal impedance Z_c :

$$Z_c = R_c + jX_c \quad (6)$$

$$R_c = \text{Re}[Z_c]$$

$$R_c = \frac{\omega\mu}{2\pi r \sqrt{\omega\mu\sigma}} \frac{\text{ber } mr \text{ bei}' mr - \text{bei } mr \text{ ber}' mr}{(\text{ber}' mr)^2 + (\text{bei}' mr)^2} \quad (7)$$

where I_0 is Bessel function:

$$m = \sqrt{\omega\mu\sigma} \quad (8)$$

$$\text{ber } mr + j \text{ bei } mr = I_0(mr\sqrt{j}) \quad (9)$$

The earth impedance is calculated with:

$$Z_g = R_g + jX_g \quad (10)$$

Mutual Impedance Z_{ij} of two conductors i and j , with their respective heights above the ground being h_i and h_j have two components. The first component is the mutual inductance L_{ij} between the two conductors when the conductors and the ground are perfectly conductive. The second component is the impedance of the earth return path that is common to the conductors i and j . The mutual impedance can be written:

$$Z_{ij} = j\omega L_{ij} + Z_{gm} \quad (11)$$

The mutual inductance L_{ij} is:

$$L_{ij} = \frac{\mu_0}{2\pi} \ln \frac{D'_{ij}}{D_{ij}} \quad (12)$$

where D_{ij} is the distance between conductors i and j , and D'_{ij} is the distance between conductor i and the image conductor j as shown in Fig.6. The impedance of the ground return Z_{gm} is:

$$Z_{gm} = R_{gm} + jX_{gm} \quad (13)$$

The correction factors defined by Carson, R_g , X_g , R_{gm} , X_{gm} are functions by parameter t and the non dimensional factor a , and is calculated with:

$$R_g = \omega\mu_0 P(a_{ii}, t_{ii}) / X_g = \frac{\omega\mu_0}{2\pi} Q(a_{ii}, t_{ii}) \quad (14)$$

$$R_{gm} = \omega\mu_0 P(a_{ij}, t_{ij}) / X_{gm} = \frac{\omega\mu_0}{2\pi} Q(a_{ij}, t_{ij}) \quad (15)$$

where:

$$a_{ii} = \frac{2h_i}{d_p}; t_{ii} = 0 \quad (16)$$

$$a_{ij} = \frac{D_{ij}}{d_p}; t_{ij} = \cos^{-1} \left(\frac{h_i + h_j}{D_{ij}} \right); d_p = \frac{1}{\sqrt{\omega\mu_0\sigma_g}} \quad (17)$$

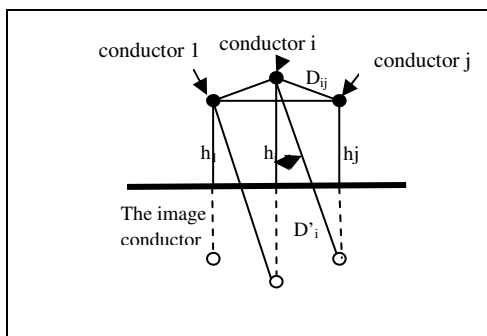


Fig. 6. Three-phase line

In functions by parameters a_{ii} can decided which series will be used:

➤ for $0 < a \leq 5$:

$$P(a,t) = \frac{1}{8} \cdot [1 - S_4(a,t)] + \frac{1}{2 \cdot \pi} \cdot \ln \frac{2}{\gamma \cdot a} + \frac{1}{2 \cdot \pi} \cdot t \cdot S_2(a,t) - \frac{1}{\pi \cdot \sqrt{2}} \cdot T_1(a,t) + \frac{1}{2 \cdot \pi} T_2(a,t) + \frac{1}{\pi \cdot \sqrt{2}} T_3(a,t) \quad (18)$$

$$Q(a,t) = \frac{1}{2} + [1 - S_4(a,t)] \cdot \ln \frac{2}{\gamma \cdot a} - t \cdot S_4(a,t) + \sqrt{2} \cdot T_1(a,t) - \frac{\pi}{4} \cdot S_2(a,t) + \sqrt{2} \cdot T_3(a,t) - T_4(a,t) \quad (19)$$

➤ for $a > 5$:

$$P(a,t) = \frac{1}{\pi \cdot \sqrt{2}} - \frac{1}{\pi} \cdot \frac{\cos(2 \cdot t)}{a^2} + \frac{1}{\pi \cdot \sqrt{2}} \cdot \frac{\cos(3 \cdot t)}{a^3} + \frac{3}{\pi \cdot \sqrt{2}} \cdot \frac{\cos(5 \cdot t)}{a^5} \quad (20)$$

$$Q(a,t) = \sqrt{2} \cdot \frac{\cos t}{a} - \sqrt{2} \cdot \frac{\cos(3 \cdot t)}{a^3} + 3 \cdot \sqrt{2} \cdot \frac{\cos(5 \cdot t)}{a^5} \quad (21)$$

The Admittance of Overhead Transmission Line. In the computation of the capacitance of transmission line accepts two factors: the length is larger then the dimensions of the circuits, the environment is uniform (air), the conductors have a cylindrical configuration.

The line capacitance:

$$C = \frac{2\pi\epsilon}{\cosh^{-1}\left(\frac{2h}{r}\right)} \cong \frac{2\pi\epsilon}{\ln\left(\frac{2h}{r}\right)} [F/m] \quad (22)$$

4. CASE STUDIES

Several numerical applications of the developed algorithm is presented in this paper. The examples focus on a 110 kV LEA and existing towers in the National Energetic System are used. The first step in this study was to validate the results obtained with the software module developed by comparison with those obtained using Alternative Transient Program (ATP) which is software dedicated to transient problems as its name says. Only the transient periods were considered for the numerical results graphic representation. The transient regime is superimposed to the rated working conditions of the high voltage line. The line structure studied is the following one:

- left termination (the source): the three phases connected on resistances of 100 MΩ (equivalent with open-end), resistance on the null wire 0.1mΩ;
- right termination (the load): the three phases connected on resistances of 100 MΩ (equivalent with open-end), resistance on the null wire 0.1mΩ
- the pulse location is the left termination of the line (green point).

The first example is the line previously considered, at the left end, lightning voltage pulse is applied. The response wave presented in Fig. 7, left side, is the signal at the open load end of the high voltage line obtained with the proposed software module. To validate the results obtained with the modul software proposed, in Fig. 7, right side, is presented the result obtained with ATP. Lightning voltage pulse shape found in the following examples is that of the ATP program (surge

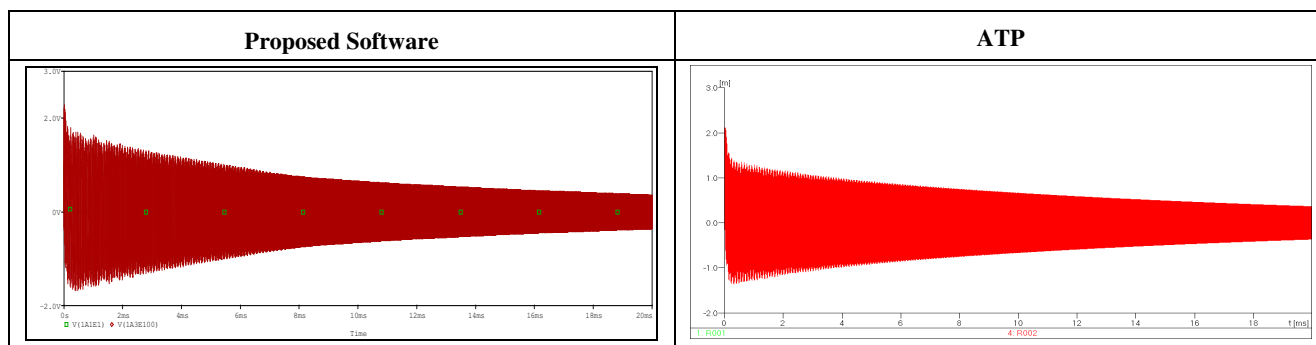


Fig. 7. Lightning pulse voltage, signal on load, 50 Hz, 100 Ωm

SOFTWARE MODUL DESIGNED FOR THE ANALYSIS OF THE LIGHTNING PROPAGATION ON OVERHEAD LINES

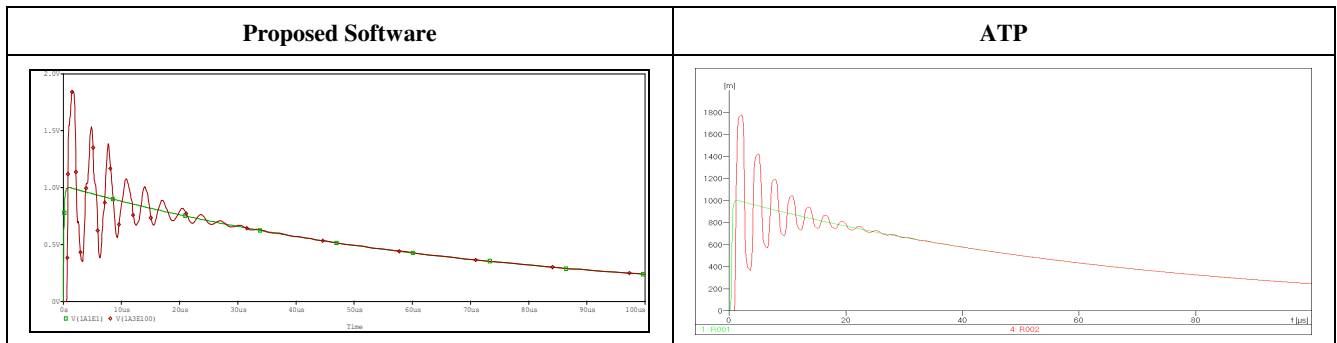


Fig. 8. Lightning pulse voltage, signal on load, 500 KHz, 100 Ω m

source). The line parameters are computed at frequency 50Hz and the ground is characterized by $\rho=100 \Omega$ m.

One can notice that if the line is with open terminals, important over-voltage of up to 200% (the over-voltage wave is twice bigger in amplitude than the initial wave) appears on the line.

In the second case when the parameters are evaluated at 500 KHz frequency (maximum possible in ATP), the wave shape of signal is presented in Fig. 8. The transient analysis in the case of a lightning voltage pulse appliance outlines a damped harmonic regime that is much more attenuate in case of parameters computed at 500 KHz. Thus, after 100 μ s, in the case of parameters computed at 50 Hz we can notice on the

load an almost sinusoidal wave. The evaluation of parameters at 500 KHz outline a significant attenuation of the signal on the load. Basically, in this case after 100 μ s the signal is completely attenuated.

If the ground is characterized by a resistivity of 1.000 Ω m can be seen that the signal waveform on load is almost identical to that obtained for the resistivity of 100 Ω m, except that amplitude is slightly smaller, so the signal attenuation will be a little faster, as seen in fig. 9. The same is observed in fig.10 where is presented the waveform on load for 10.000 Ω m soil resistivity.

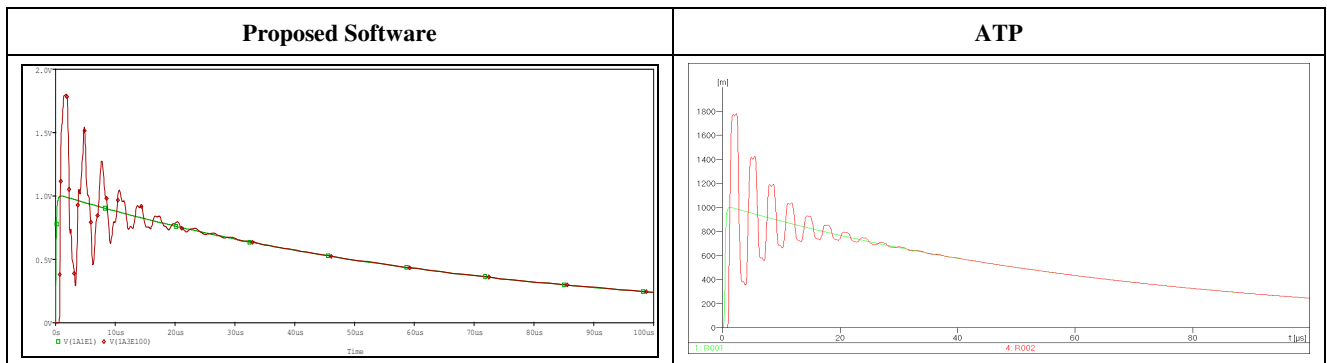


Fig. 9. Lightning pulse voltage, signal on load, 500 KHz, 1.000 Ω m

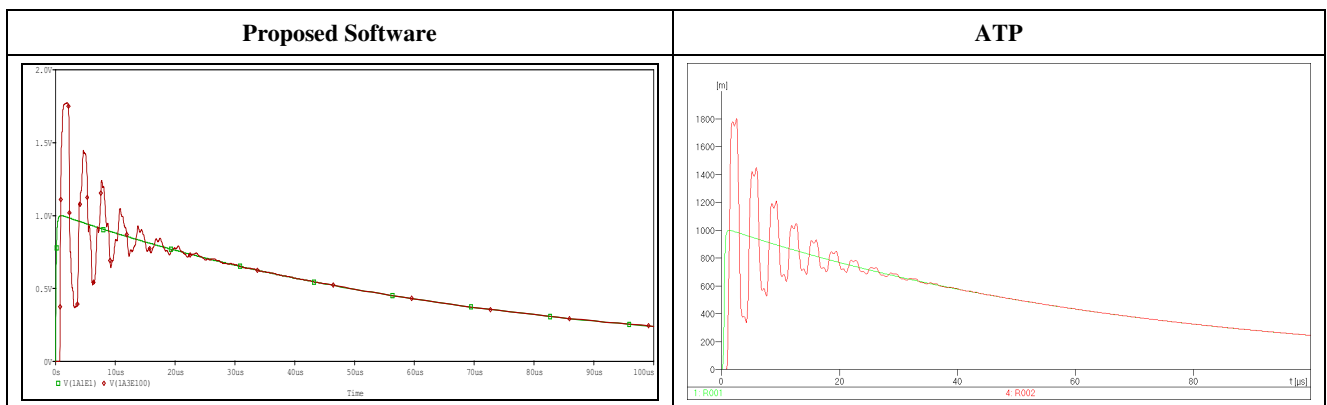


Fig. 10. Lightning pulse voltage, signal on load, 500 KHz, 10.000 Ω m

5. CONCLUSIONS

✓ The paper proposes numerical computation software for analysis of transient propagation on high voltage lines. In order to take into account the influence of the loss ground in case of high frequency signals on the high voltage line, the Carson's formulas were considered for the per unit length parameters computation.

✓ The numerical analysis of the equivalent circuit is done using a Pspice-based computation module. The flexibility offered by the algorithm due to the facilities included and by using professional circuit analysis software allow handling a great number of practical situations.

✓ The conclusion of the analysis performed is that the appearance of a voltage pulse on one phase of the HV LEA conductors generates significant over-voltages.

✓ Regarding the influence of the ground presence on the parameters computation, one can conclude that: the value of the resistance correction becomes significantly important in the total value of the resistance for frequencies higher than 10^3 Hz. For inductance important correction are to the small frequency values.

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