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LIGHTNING-INDUCED OVERVOLTAGES IN OVERHEAD POWER DISTRIBUTION LINES: IMPORTANCE OF THE LINE GROUNDING ELECTRODES MODELING

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Abstract — Models for the calculation of lightning-induced voltages on distribution networks, should be able to take into account the presence of shielding wires and/or neutral conductors and of their relevant groundings. The paper deals with the estimation of the influence of these groundings with particular reference to the grounding electrode model on the calculated values of the lightning-induced voltages.

Index Terms — Lightning-induced overvoltages, line grounding, shielding wire, EMTP, lightning outages.

1 - INTRODUCTION

The availability of a model of LEMP-illuminated lines able of treating realistic line configurations is of utmost importance for the assessment of the lightning/power quality performance of such systems. The two main counter measures against lightning induced overvoltages for overhead distribution lines are the use of surge arresters or the adoption of periodically-grounded shielding wires; this makes the configuration of the system to be simulated certainly complex [1]. In this paper we shall deal with the second mitigation method and we shall focus, in particular, on the influence of the modeling of the line groundings.

2 - COMPLEX LINE GROUNDING MODEL

Analysis of lightning-induced transients in electric power systems requires careful modeling of each part of the system: here the attention is given to the groundings of the shielding wire. In the technical literature, the evaluation of the current distribution in both aerial and buried electrodes is generally carried out by means of numerical codes based on either circuit models or on field approach.

When dealing with fast transients, the frequency range covered by the transient of interest is of crucial importance for the appropriate choice of the model to be adopted. The significant frequency range of transients due to lightning electromagnetic pulses (LEMP) is 10 kHz ÷ 10 MHz.

In this respect, the field approach represents the most rigorous way to take into consideration the electromagnetic phenomena associated with LEMP [2,3]. However, the evaluation of electromagnetic interference among buried and aerial electrodes by means of such an approach can be extremely time consuming.

On the other hand, in the lumped parameters approach [4-6], which is less time consuming, when grounding systems are of complex geometry, the elements of the equivalent electrical network may be complex to be inferred.

Although, from a theoretical point of view, some criticisms have been addressed to the lumped parameters approach [7], recent works conclude that, in case it be appropriately applied, such an approach – which is an acceptable compromise between computational time and accuracy of the results [8] – can be adopted.

In this paper we shall investigate the influence of different grounding system models on the LEMP-response of an overhead distribution line.

A first grounding system model, based on the lumped parameters representation, will be used. In it, each elementary segment is modeled with an equivalent p model, where self and mutual inductances and transverse conductance are the parameters of major concern (Fig. 1). As discussed in [4], this kind of cell possesses the best frequency response for the representation of the elementary section of the buried wire. Therefore, the whole grounding electrode is represented through an equivalent electric circuit formed by a cascade of these p cells. The most important parameters of the model are the following:

- ·*r*, the longitudinal resistance of the electrode;
- ·*L*, *M* the self and mutual inductance (magnetic coupling with other electrode segments);
- ·*c* and *g*, the capacitance and conductance to earth;
- ·*c'* and *g'*, the capacitance and conductance between different electrodes.

The interactions deriving from the coexistence of a number of grounding electrodes can be taken into account by means of suitable Current Controlled Voltage Sources (CCVS) introduced between the transversal conductance and the earth. These CCVS are controlled by the current leaked to earth from the electrodes into which the grounding system has been discretized [4].

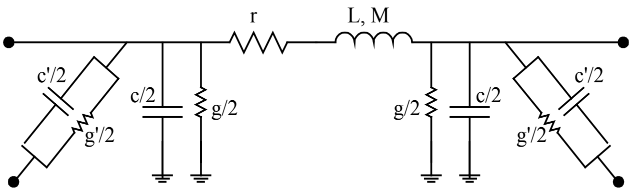


Fig. 1. Elementary π cell for lumped parameters models.

A second alternative approach, based on a finite element analysis to model parts that compose the earth embedded electrodes, proposed by Meliopoulos et al. [9], will be used in this paper too. Short elements of buried electrodes are characterized as transmission lines with distributed inductances, capacitance and leakage resistance to earth (Fig. 2). Each element of the model can be accurately calculated: the leakage resistance by means of the method of moments, while inductances and capacitance can be computed from the resistance by means of Maxwell's equations.

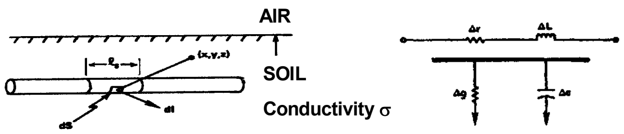


Fig. 2. Single conductor buried in uniform soil and representation of a finite element with circuit elements. Adapted from [9].

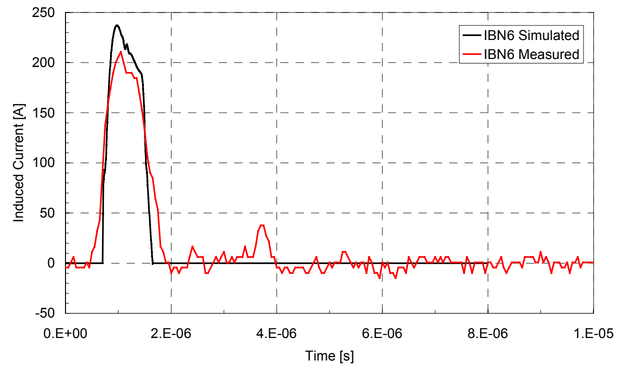
Both above models have been previously implemented in the EMTP. A third, simple model, will be also used. It consists of a lumped resistance corresponding to the low frequency value of the grounding system.

3 - ESTIMATION OF LIGHTNING-INDUCED OVERVOLTAGES ON OVERHEAD DISTRIBUTION LINES IN PRESENCE OF SHIELDING WIRE PERIODICAL GROUNDINGS

The models above described have been also included in the LIOV (lightning induced overvoltage) code [6]. The LIOV code has been developed in the framework of an international collaboration involving the University of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome "La Sapienza" (Department of Electrical Engineering). The LIOV code is based on the field-to-transmission line coupling formulation of Agrawal et al. [10], suitably adapted for the case of an overhead line illuminated by an indirect lightning electromagnetic field. The equations are numerically solved by a finite difference time domain (FTDT) approach. More recently, a 2nd order FDTD integration scheme has been applied [11] in order to improve the numerical stability of the code. The return stroke electromagnetic field is calculated by assuming the MTLE engineering model and using the Cooray-Rubinstein formula for the case of lossy grounds [12-15].

The LIOV code has been interfaced with EMTP96 in order to make it possible to deal with realistic line configurations [17,18] and, specifically, with multi-conductor overhead line with shielding wires and/or neutral conductors grounded at same points along the line. Voltages induced by indirect lightning along such a line can be calculated by introducing an ad-hoc modification of the above-mentioned coupling model [1,11].

a)



b)

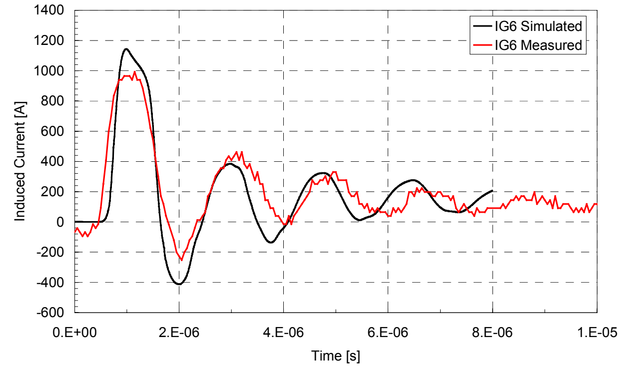


Fig. 3. Comparison between experimental and simulation results for the 6th return stroke of the lightning flash triggered on August 2, 2003 (current amplitude: 19.6 kA, maximum time derivative: 110 kA/μs) at the ICLRT: a) induced-current flowing through the arrester located at the line pole closest to the stroke location (pole 6), between phase B and neutral conductors, b) induced-current flowing through the grounding of the same line pole. The stroke location (rocket launching station) is 15 m from one end of the line. Adapted from [16].

Concerning the representation of the grounding points of the shielding wire, two possible solutions have been proposed [1,11,17]. The first one, discussed in the Appendix [1,11], concerns the modification of the coupling model to take into account the presence of periodical grounding; the second one [11,17], used to obtain the results presented in this paper, consists of implementing the complex grounding models described in Section II above, in the LIOV-EMTP96 code.

The LIOV-EMTP code has been successfully tested against experimental results obtained through EMP simulators [11] and real scale experiments [16]. In particular, Fig. 3 presents a comparison between the experimental data and the simulation results obtained by using the LIOV code relevant to the 0.75 km long experimental line installed at the International Centre for Lightning Research and Testing (ICLRT [20]) of the University of Florida, composed of 4 conductors (3–phase conductors plus neutral periodically grounded) and equipped with surge arresters and 500 Ω resistors at the line terminations.

The groundings of the neutral conductors, composed by cylindrical vertical rods and placed at five different poles of the line, are modelled adopting a lumped parameter approach whose equivalent circuit is shown in Fig. 4.

As it can be seen, the numerical results shown in Fig. 3 obtained using the LIOV code are in good agreement with the measurements.

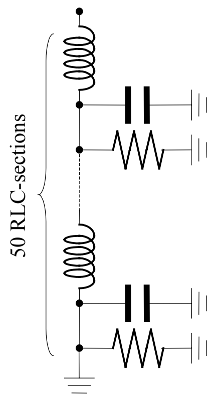


Fig. 4. Lumped parameters representation of grounding rods adopted for the calculations of Fig. 3.

4 - ANALYSIS OF THE LINE GROUNDING ELECTRODES MODELING ON THE EVALUATION OF LIGHTNING-INDUCED OVERVOLTAGES

4.1 - GEOMETRY ADOPTED FOR THE SIMULATIONS

To better assess the effect of the shielding wire, of the distance between two consecutive groundings and of the model adopted for the grounding resistance on the amplitude of the induced voltages, we have considered the line geometry shown in Fig. 5 in which only the shielding wire and one phase conductor are present.

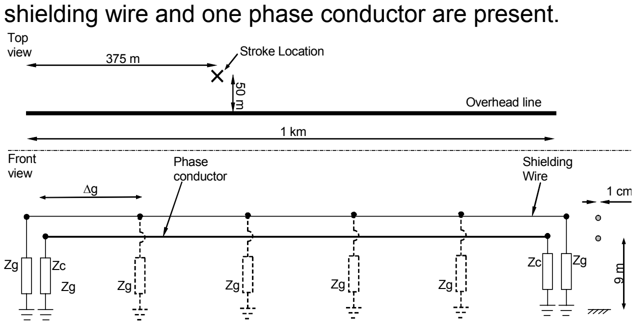


Fig. 5. Line geometry adopted to evaluate the effect of the presence of a shielding wire. Lightning current: peak value 12 kA maximum time derivatives: 12, 40 and 120 kA/μs.

Different distances between line groundings are considered, namely: 1 km (groundings placed at line terminations), 500 m (groundings placed at line terminations and at line center) and 200 m.

As shown in Fig. 5, the considered lightning stroke location does not 'face' any of the grounding resistances.

In order to investigate the behavior of different grounding model with the frequency of the lightning electromagnetic field, simulations have been carried out for three different lightning current waveshapes, with the same peak value of 12 kA and maximum time derivatives of 12, 40 and 120 kA/μs.

The presence of lossy ground is taken into account in the grounding electrode models and in the calculation of the electromagnetic field using the Cooray-Rubinstein formula [12-15]. The ground conductivity value is considered equal to 0.01 S/m.

In order to compare the results of the two considered grounding system models, a 20 m long horizontal electrode (counterpoise), buried at 0.6 m depth and with a radius of 0.5 cm, has been considered connected to every shielding wire grounding. In a first approximation, the electromagnetic coupling between the LEMP and the grounding system conductors has been disregarded. Further works is certainly needed is this respect to better assess the validity of such an assumption.

For the case of the lumped parameters model of the type mentioned in Section II, each electrode has been divided into forty 0.5m long elementary segments, each represented with the same number of p cells connected in series.

In the simulations, also a simplified grounding model consisting of a single lumped resistance has been considered. Its value has been estimated with reference to the already mentioned low frequency value of the counterpoise resistance equal to 8.5 Ω.

4.2 - SIMULATION RESULTS

In this section the effect on lightning-induced voltages of the type of grounding electrode model is examined.

Fig. 6 and 7 show– for the considered lightning current waveshapes – the amplitudes of the induced overvoltages on the shielding wire and on the phase conductor at ten observation points placed along the line each 100 m, for the three different grounding models: distributed parameter, lumped parameters representation and single lumped resistance grounding model.

For all the grounding model, the mitigation effect of the shielding wire depends significantly on the spacing between two consecutive groundings. As already observed in [1,11], an effective protection of the phase conductor can be achieved only if the spacing between two consecutive groundings is of 200 m. For larger values of spacing, only the portion of the line in the immediate vicinity of the grounding points appears to be protected.

Fig. 6 and 7 show that the differences between the lightning induced voltages calculated using the distributed parameter grounding model and the lumped parameters representation are negligible, for both the shielding wire and the phase conductor. This result supports the adequacy of the lumped parameters representation for the problem of interest, at least as far as the coupling between the grounding elements and LEMP are disregarded. On the contrary, the adoption of the single lumped resistance grounding model results in induced voltage values that significantly differ with respect those calculated by using the other two models, for the cases in which the distances between line groundings are of 200 m and the maximum time derivatives of the lightning currents are larger than the typical median value (40 kA/μs).

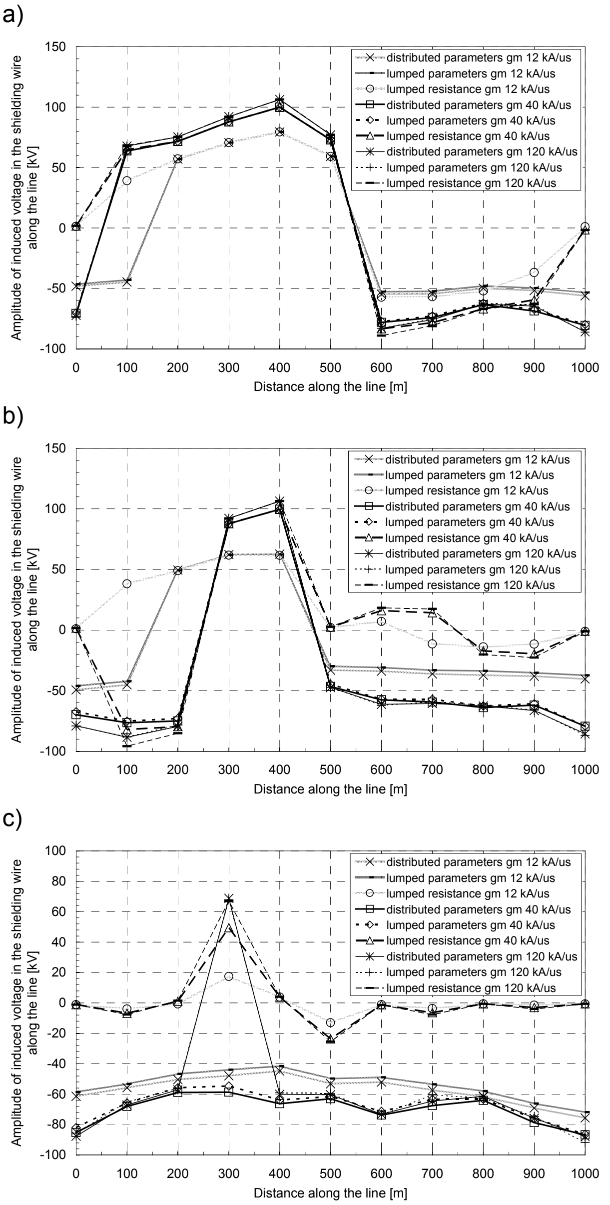


Fig. 6. Amplitude of the induced voltage in the shielding wire along the line for a variable grounding step. Line configuration of Fig. 5. Stroke location at 375 m from the left line termination. Lossy ground σ_g=0.01 S/m; a)Δ_g=1000 m, b)Δ_g=500 m, c)Δg=200 m.

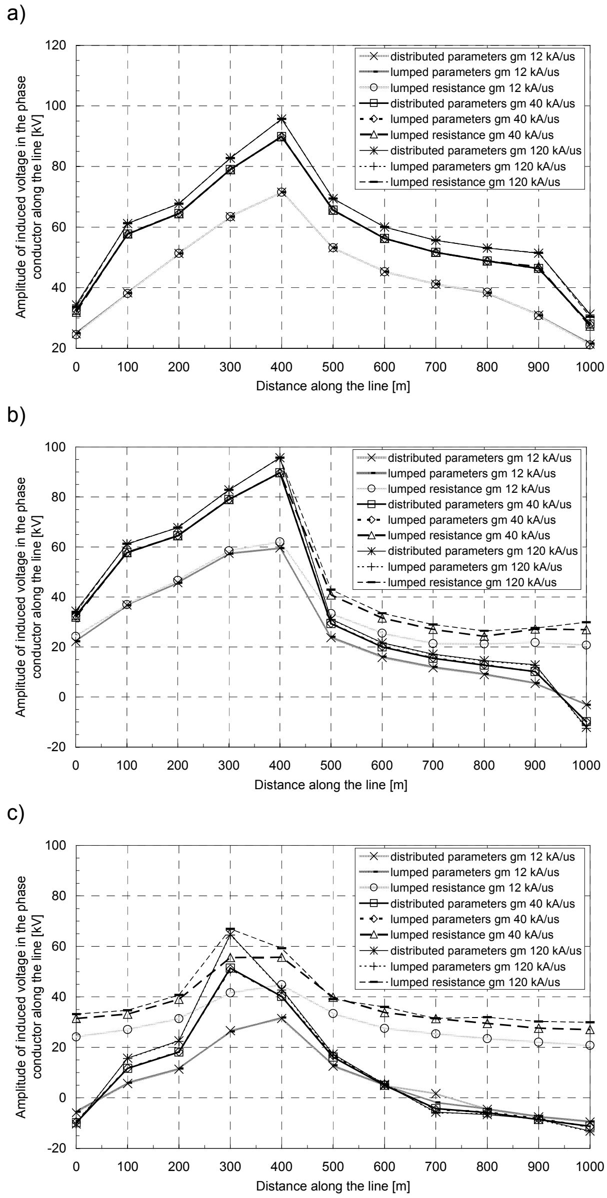


Fig. 7. Amplitude of the induced voltage in the phase conductor along the line for a variable grounding step. Line configuration of Fig. 5. Stroke location at 375 m from the left line termination. Lossy ground σ_g=0.01 S/m; a)Δg=1000 m, b) Δg=500 m, c) Δg=200 m.

We can further observe that, both in the shielding wire and in the phase conductor, the differences among the voltages calculated by using the three different grounding models tend to increase with the increase of the lightning current maximum time-derivative. For a current with maximum time-derivative of 120kA/μs, the maximum difference between the voltages on the phase conductor calculated using the single lumped resistance model and the other two models is of the order of 50 %.

5 – CONCLUSIONS

Differences between lightning induced voltages calculated using the considered grounding models exist only for the case of distances between line groundings of 200 m. These differences are more sensible for large values of the lightning current maximum time-derivative.

The representation of the shielding wire grounding as a single lumped resistance is equivalent to the other two more complex models only for distances between line groundings larger than 200 m and for typical values of the maximum time-derivatives of the lightning currents. For fast rising lightning currents it may be advisable the adoption of a more accurate model.

Coupling between LEMP and grounding elements, disregarded in this paper, is being investigated in order to assess the adequateness of such an assumption.

6 – APPENDIX

Section III describes the representation of periodical shielding wire grounding of a LEMP-illuminated line using the LIOV-EMTP96 code; a different modeling of such an illuminated line consists on the modification of the Agrawal et al. coupling model using the approach presented in [1,11].

Let us consider an overhead multi-conductor line above a lossy ground provided with shielding wires. The scattered voltages, at node *g* were a grounding point is placed, can be expressed as follows (see Fig. A.1):

$$\left[v_i^s\right] = \left[\Gamma_{ij}\right]\left[i_{g,i}\right] + \left[\int_0^{h_i} E_z^e(x,z,t)dz\right] \qquad \text{(A.1)}$$

where Γ is an integro-differential operator which describes the voltage drop across each impedance connected between the conductor i and the ground, as function of current $i_{g,i}$ given by the grounding electrode complex model (described in previous paragraph). As the Agrawal model is expressed in terms of the scattered voltage $\left[v_i^s\right]$, it is necessary to include a voltage source in series with the impedance, the so-called incident voltage expressed by $\left[\int_0^{h_i} E_z^e(x,z,t)dz\right]$, which is given by the integral from the ground level to the line conductor hi of the incident vertical electric field $E_z^e(x,z,t)$ (see Fig. A.1).

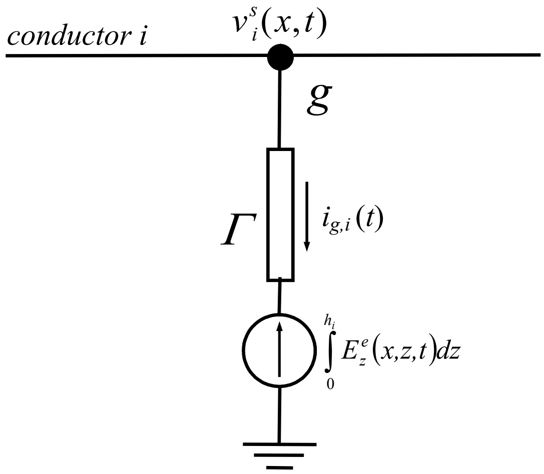


Fig. A.1. Insertion of a grounding in a generic point along a multi-conductor line.

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