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Equivalent Lumped Parameter Π-Network of Typical Grounding Systems for Linear and Non-Linear Transient Analysis

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Abstract--**In this paper, the authors propose and validate a simple lumped parameter model based on a π-type network. This model is able to simulate the ground potential rise of typical tower grounding systems under surge conditions. The lumped parameter values are estimated by means of an optimization procedure based the micro-genetic algorithm (μGA). This procedure minimizes the standard deviation between target values (obtained using a full circuit model able to perform frequency domain analyses and time domain analysis under linear and non-linear conditions) and simulation results (obtained using the equivalent π-network model). The proposed model has been validated by means of massive simulations of typical Italian 380 HV transmission line grounding systems under surge conditions (varying impulsive current wave shapes, grounding system geometrical configurations, soil characteristics and also accounting for non-linear ionization phenomena). The simulation results have always revealed a very good agreement between target values and model results. In addition, the proposed π-network model drastically reduces the computational resources required for linear and non-linear transient analyses of typical tower grounding systems.**

Index Terms—**Grounding System, Soil Ionization, Circuit Model, Transient Analysis, Genetic Algorithms.**

I. INTRODUCTION

EXPERIMENTAL results [1]-[3] and numerical simulations [4]-[13] of typical tower grounding systems excited by lightning currents have shown that transient responses are affected by marked inductive behaviours and non-linear ionization phenomena. In order to obtain a correct design of electrical systems, with respect to the protection of installations against anomalous events, it is fundamental to predict the impulse characteristics of grounding systems [14]-[15]. In particular, the accurate simulation of the non-linear transient behaviour of these groundings became a fundamental task in parametric studies related to, e.g., backflashover simulation of HV transmission lines [16]-[18] or direct lightning of the transition tower of long mixed overhead-cable EHV lines [19]-[21]. Although, several respected models are available in literature [5][8][9][13], the circuit ones [2]-[4][6]-[12] have been those mainly used to simulate complex power systems in which the grounding system is only one of the components, even if they are very computational expensive when non-linear cases are analysed. In addition, the non-linear circuit model can be easily coupled with power system models developed by means of transient electromagnetic programs such as ATP [11]. These models generally provide accurate results for very complex scenarios [14]-[21]. However, the main drawback of such models, especially if statistical analyses must be carried out (e.g., the evaluation of backflashover rate, BFOR, by means of Monte Carlo methods), is the request of large computational resources (i.e., memory occupation and execution time). In order to drastically reduce this drawback, the authors propose a procedure able to represent the ground potential rise (GPR) of typical tower grounding systems by an equivalent π-network.

Recent studies have demonstrated that extended grounding systems under surge conditions (such as simple horizontal wires pulsed by severe lightning current wave-shapes) may be represented by a simple equivalent π-network for linear and non-linear cases [22]. In this paper, it will be investigated the possibility to generalize this approach, fitting the input transient impedances of typical Italian HV transmission line grounding systems (Fig. 1) by equivalent lumped parameter π-type networks.

II. SIMPLIFIED GROUNDING SYSTEM CIRCUIT MODEL

The typical Italian HV transmission line grounding systems go from short stepped counterpoises to a distinctive crowfoot geometry, the configuration becoming more involved with increasing of soil resistivity (Fig. 1).

The simulation models of such kind of systems in surge conditions are, generally, very expensive in terms of memory occupation and execution time, because of the non linearities introduced by soil ionization phenomena [14]-[21].

A. Non-linear ionization phenomena

When ionization phenomena occur, the distribution of the electric field along the surface of the earth electrodes generates local transversal discharges, which produce intense ionization around the electrodes and cause the non-linear response of the grounding system. In order to obtain a correct design of electrical systems, with respect to the protection of installations against anomalous events, it is fundamental to predict the impulse characteristics of grounding systems.

In previous papers [2]-[6], the authors have already described in detail an equivalent circuit model used for the simulations of simple and complex grounding systems when

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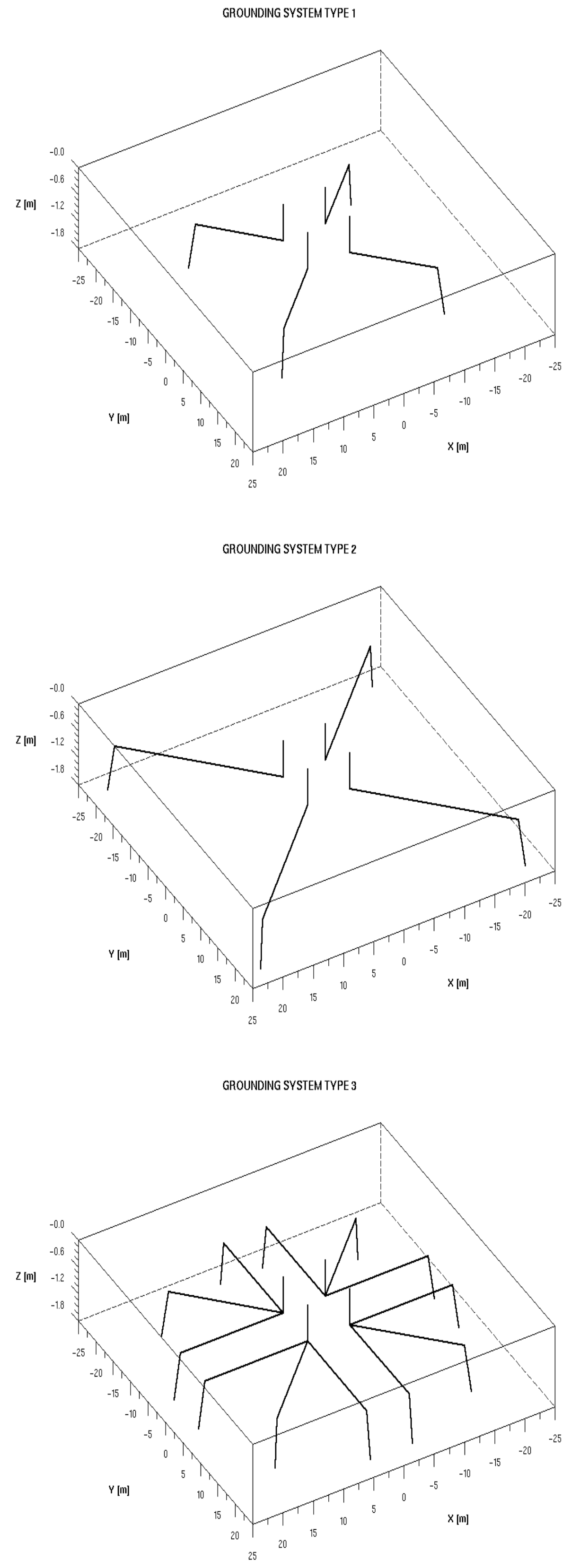

GROUNDING SYSTEM TYPE 1

GROUNDING SYSTEM TYPE 2

GROUNDING SYSTEM TYPE 3

Fig. 1. Sketch of typical Italian 380 kV transmission line grounding systems (named benchmark grounding systems) consisting of horizontal branches (numbering from 4 up to 12) made of strap iron (FE 360 B, 40 x 4 mm^2, $\rho_{Fe} = 0.1\ 10^{-6}\ \Omega$m) buried at about 0.8 m; branch terminals, 1.4 m long, have a 45° slope. [Grounding system: Type 1 - $\rho_g = 500\ \Omega$m, $\varepsilon_r = 43$; Type 2 - $\rho_g = 1000\ \Omega$m, $\varepsilon_r = 35$; Type 3 - $\rho_g = 2000\ \Omega$m, $\varepsilon_r = 19$]

non-linear ionization phenomena take place. The model has been validated by comparing the numerical results with experimental tests [2][3] and with simulation results yielded by more sophisticated models [9][13]. In addition, this model has been included within extended and detailed studies of power systems under transient conditions [14]-[21].

So the authors have considered the simulation results of this equivalent circuit model, from now on named the "exact model" (and then, the numerical values provided by this model will be also named the "exact solution"), as a benchmark for the performances of the new simplified π-network model.

B. Micro-Genetic Algorithm (μGA)

The estimation of the equivalent π-network parameters, fitting the GPR of an extended grounding system, is not a simple task, since soil ionization makes the transient analysis of such systems non linear. For this reason an optimization procedure based on a particular genetic algorithm (GA) [23], named micro genetic algorithm (μGA) [24][25], has been implemented [22].

The μGA is a non-deterministic optimization procedure developed to improve GAs performances, in terms of computational efficiency and goodness of the optimal solution [23]-[25], by reducing the population size generally to four or five individuals. The μGA searches for an optimal solution using the principles of evolution and heredity, operating on populations consisting of individuals each representing a solution, which are a particular selection of variable values (coded in several bit strings named chromosomes).

Starting from a randomly generated initial population, new solutions are generated by effect of the genetic operators of "crossover" and "mutation", which mimic the evolution process occurring in the nature; the fitness of each individual is obtained by evaluating the objective function to be optimized and this provides the μGA with the necessary evolutionary drift towards the optimum. At each iteration it is convenient to identify the best individual, which is transferred to the next generation ("elitism" operator); in addition, the genetic diversity of the population is checked and a periodic restart of the procedure, with randomly generated individuals, is made.

The μGA operates according to the eight-point iterative procedure described below and outlined in the flowchart of Fig. 2:

1. encoding the equivalent π-network parameters as genes;
2. creation of chromosomes as strings of genes;
3. randomly initialization of a starting population;
4. evaluation and assignment of fitness values to each individual of the population (by comparing the "exact solution" with the numerical results computed with the equivalent π-network parameters collected in each individual);
5. reproduction by means of fitness-weighted selection of individuals belonging to the population;
6. recombination to produce recombined members;
7. evaluation and assignment of fitness values to the individuals of the next generation (as described in point 4);
8. convergence check and possible restart from point 3 of this procedure.

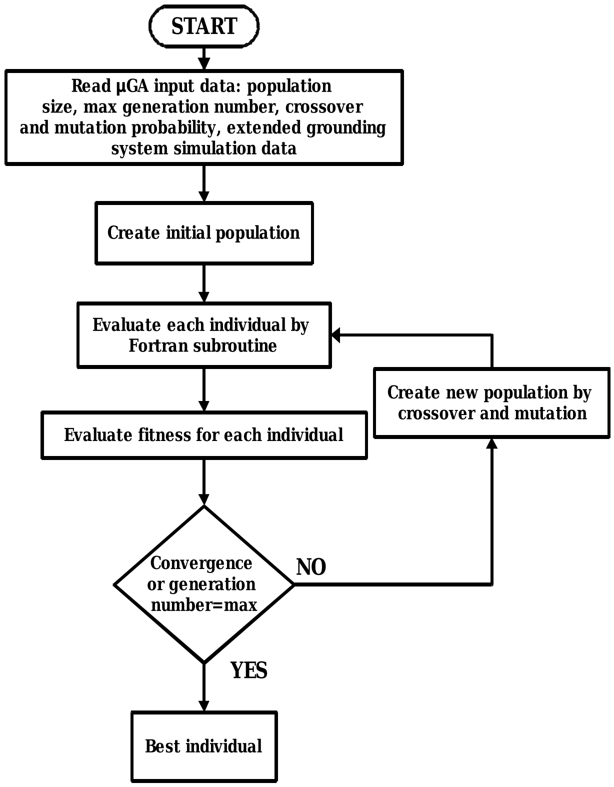


Fig. 2. Flowchart of the optimization procedure based on µGA.

C. *Π-Network Linear Grounding System Model*

The steady-state behaviour of extended grounding systems has been studied by means of frequency scan (FS) ATP/EMTP analyses [22] using the "exact" model in order to evaluate the grounding system input impedance, in a 1 Hz ÷ 1 MHz range. In order to simulate such behaviour with a simple circuit model, the authors have proposed the equivalent π-network shown in Fig. 3a. The circuit parameters (the shunt resistors and capacitors R_1, R_2, C_1, C_2 and the longitudinal resistor R_3 and inductance L) of the equivalent π-network have been estimated by coupling the µGA, described in the previous paragraph, with a simple FORTRAN routine [22], which calculates the input impedance of the equivalent network, and then by minimizing the fitness function, which calculates the standard deviation between the input transient impedance of the extended grounding system (evaluated by means of ATP simulations) and the input transient impedance of the π-network (calculated by means of the FORTRAN routine), according to the flowchart outlined in Fig. 2.

D. *Π-Network Non-Linear Grounding System Model*

In order to take in consideration the soil ionization, that occurs with high lightning currents and that makes the grounding system response non-linear, the authors have introduced, in parallel to the resistors R_1 and R_2 of the equivalent π-network (Fig. 3a), two ideal voltage controlled current sources G_1 and G_2 (Fig. 3b).

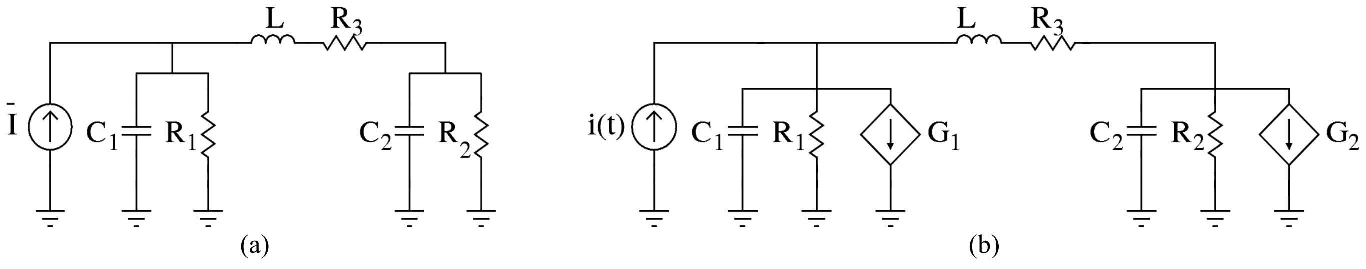
These generators simulate all non-linearities associate to ionization phenomena. They have been characterized by means of the same procedure outlined in the flowchart of Fig. 2. In this case, the procedure minimizes a fitness function given by the standard deviation between the GPR computed using the "exact model" (implemented by an ATP program [11]) and that computed using the equivalent π-network model (simulated by a FORTRAN routine able to solve the circuit in Fig. 3b). The computations have been performed on a wide range of impulsive current wave-shapes (simulated both by double exponential functions and by the Heidler functions) varying the current peak, I_p, the time-to-front, T_f, and/or the tail time, T_t, values.

III. Numerical Results

The simulated tower grounding systems closely follow a "family" of such structures designed by an important Italian TSO, for use in medium-to-high resistivity soils (up to ρ_g = 2000 Ωm). Geometry and physical details are shown in Fig. 1. Generally speaking, with increasing of soil resistivity the simulated grounding systems become more involved, going from short stepped counterpoises to a distinctive crowfoot geometry (for resistivity higher then 2000 Ωm, special arrangements were made, including the installation of long counterpoises). In particular, the operation conditions of the three configurations simulated (Fig. 1) are the following:

1. Type 1 is designed for the soil resistivity range ρ_g = 300÷600 Ωm, with each branch projecting horizontally about 14 m from tower foot;
2. Type 2 is designed for the soil resistivity range ρ_g = 600÷1300 Ωm, with each branch projecting horizontally about 26 m from tower foot;
3. Type 3 is designed for the soil resistivity range ρ_g = 1300÷2000 Ωm, with each branch projecting horizontally about 18 m from tower foot.

All grounding system types has been studied in frequency domain and in time domain, in order to evaluate the best parameter choices fitting linear and non-linear responses of the "exact model" and, at the same time, to verify the generality of these choices for each grounding system type.



(a) (b)

Fig. 3. Equivalent lumped π-network: a) for steady state analyses in the frequency domain and linear analyses in the time domain; b) for non-linear transient analyses in the time domain.

A. Steady State Frequency Domain Analyses

The results of the steady-state frequency analysis, in a 1 Hz ÷ 1 MHz range, are shown in Fig. 4. For each grounding system type, the results of the “exact model” (obtained by FS ATP/EMTP analyses) have been compared with those computed by means of the equivalent π-network of Fig 3a (which has been simulated by a simple FORTRAN program).

B. Time Domain Linear Transient Analyses

The equivalent π-network parameters, obtained by means of steady-state frequency analyses, have been tested under surge conditions. A large number of time domain linear transient analyses have been carried out to verify the π-network model performances and accuracy. For each grounding system type and for each excitation current, the GPR of the “exact model” (obtained by ATP/EMTP simulations) has been compared with that evaluated by means of the equivalent π-network model (simulated by a simple FORTRAN program). All these computations have been executed by varying the impulsive current wave-shapes (simulated both by double exponential functions and by Heidler functions). An example of this time domain linear transient analysis is shown in Fig. 5.

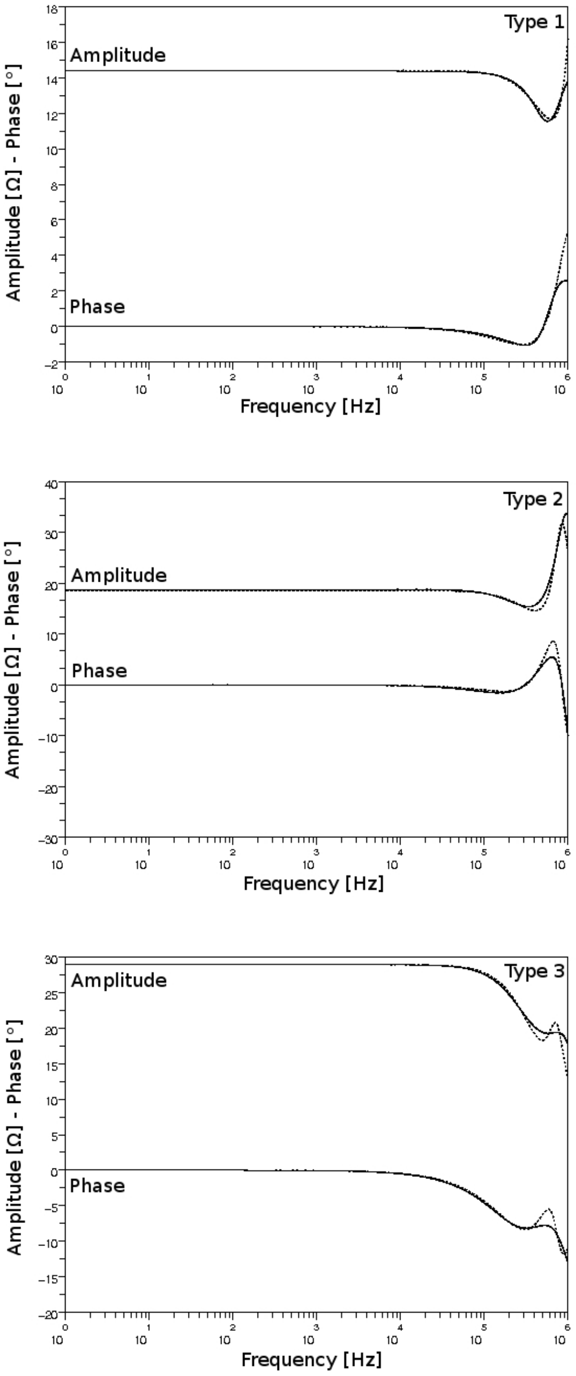


Fig. 4. Frequency scan in a 1 Hz÷1 MHz range of grounding systems Type 1, 2 and 3. [Legend: “exact solutions” - dotted lines; π-network simulation results - continuous lines]

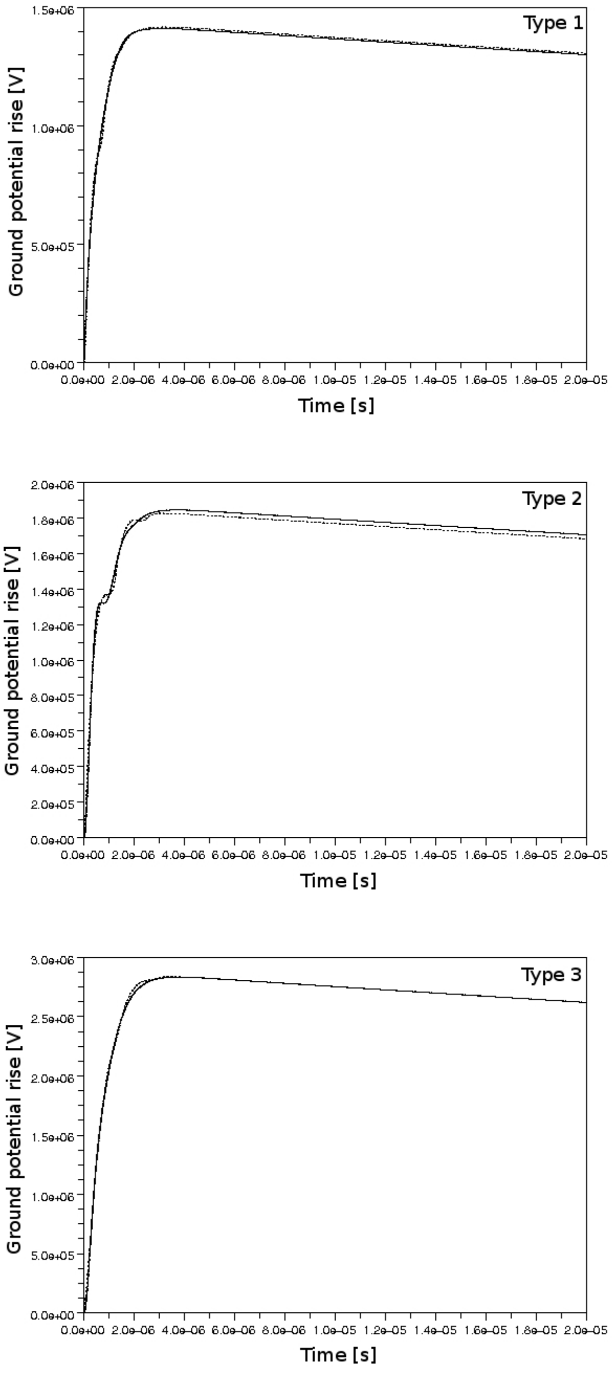


Fig. 5. Linear transient analysis of grounding systems Type 1, 2 and 3 excited by the double exponential function: 100 kA - 1.331/750 µs. [Legend: “exact solutions” - dotted lines; π-network simulation results - continuous lines]

C. *Time Domain Non-Linear Transient Analyses*

The ideal voltage controlled current sources G_1 and G_2 (Fig. 3b) have been defined, as describe in § II.D, and by means of time domain non-linear transient analyses carried out referring to assigned excitation current wave-shapes.

In order to verify the π-network model performances and accuracy a large number of time domain non-linear transient analyses have been also carried out by varying the impulsive current wave-shapes (i.e., by varying the current peak, I_p, in a 80÷110 kA range, the time-to-front, T_f, in a 0.992-1.675 µs range and/or the tail time, T_t, in a 690-800 µs range) simulated both by double exponential functions and by Heidler functions. For each grounding system type and for each excitation current, the GPR of the "exact model" (obtained by ATP/EMTP simulations) has been compared with those evaluated by means of the equivalent π-network model (simulated by a simple FORTRAN program). In particular, the study of the equivalent π-network was made by a simple FORTRAN subroutine implementing the Euler method and it is solved instantaneously. Moreover, the ATP/EMTP implementation of a simple π-circuit does not require any memory or execution time effort. Some examples of time domain non-linear transient analyses are shown in Fig. 6.

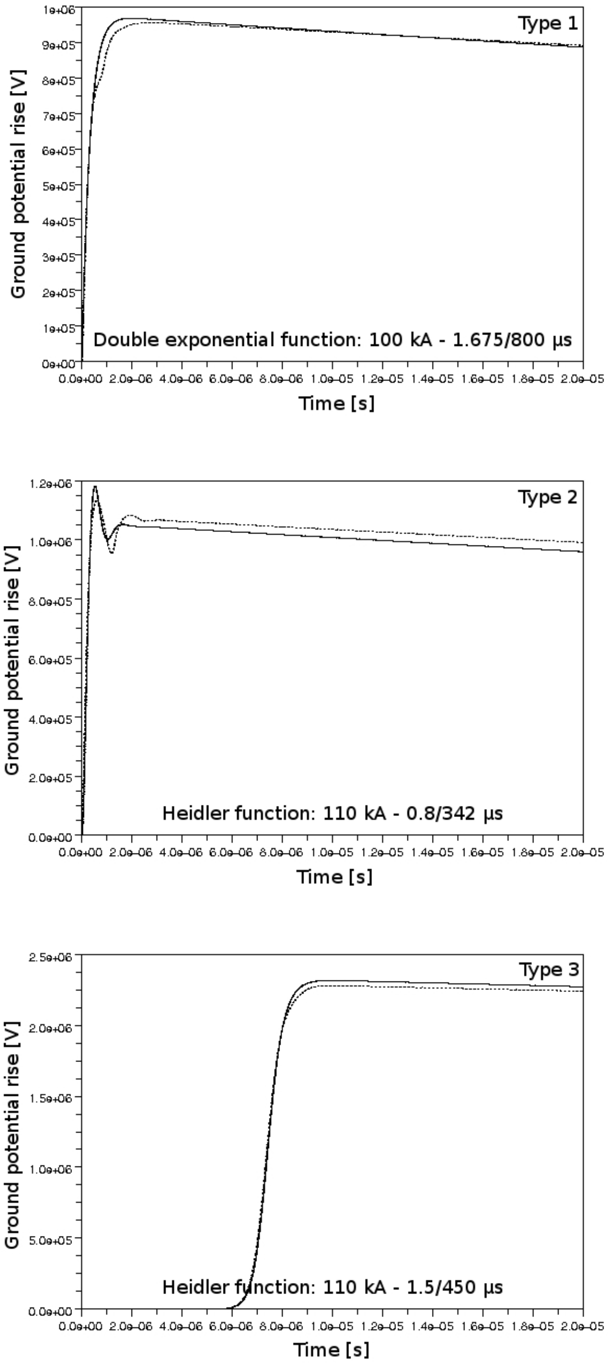


Fig. 6. Non-linear transient analysis of grounding systems Type 1, 2 and 3. [Legend: "exact solutions" - dotted lines; π-network simulation results - continuous lines]

D. *Analysis of the results*

The steady-state frequency analyses (Fig. 4) of the proposed lumped parameter π-network model is in a very good agreement with FS "exact solutions", for all grounding system types and for all supply frequencies up to 1 MHz (which is the typical highest frequency in transient analyses involving lightning phenomena).

The skill of the concentrated model to simulate the inductive and capacitive responses of an extended grounding system has been well investigated by time domain linear transient analyses having very "fast" impulsive current wave-shapes. In all cases, a good agreement between exact solutions and simulations results have been achieved, as Fig. 5 also demonstrated.

The definition of voltage controlled current generators G_1 and G_2 (Fig. 3b), by means of the µGA optimization procedure, also gives acceptable results when soil ionization phenomena must be simulated. For some relevant case studies, GPR evolutions have been plotted in Fig. 6, comparing "exact solutions" and π-network model results. The curves always present an acceptable agreement.

IV. CONCLUSIONS

In this paper the authors have proposed and validated a simple lumped parameter model based on a π-type network. This model is able to predict the GPR of typical tower grounding systems during the draining to earth of high lightning currents, also when non-linear ionization phenomena occur. The prediction of the equivalent lumped parameters was performed by means of an optimization procedure based on µGA. This procedure minimizes the standard deviation between target values (computed referring to benchmark grounding systems by means of a complete and accurate circuit model able to carry out both frequency domain analyses as well as linear and non-linear time domain analyses) and simulation results (obtained by running the equivalent π-network model). Then the proposed simplified model has been validated by means of massive simulations of typical Italian HV transmission line grounding systems varying lightning current wave-shapes. The simulation results have always revealed a very good agreement between target values and those obtained by the corresponding π-circuit model. In addition, as demonstrated by several case studies carried out, the proposed π-network model drastically reduces the computational resources required for linear and non-linear transient analyses of tower grounding systems without losing in accuracy. This is a very good feature, especially when complex power systems, of which the grounding system is only a part, must be studied in transient conditions (e.g., in all studies related to backflashover analyses – typically, BFOR – or, more in general, to lightning response of HV transmission lines).

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