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Experimental study of transient behaviour of grounding grids using scale models

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Abstract

This work aims at studying and investigating the transient behaviour of the grounding grids under impulse lightning currents using scale models in an electrolytic tank. Impulse current tests were performed on several types of grids. The injected current in the grounding grid and the developed potential were recorded, resulting in the determination of the variation of the grid transient impedance versus time. Finally, the variation of the parameters of the impulse impedance in relation to the injection point for various grids, depths and conductivities is investigated.

Keywords: grounding system, grounding resistance, impulse impedance, transient behaviour, measurements, electrolytic tank

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The factors that affect the transient behaviour of the grounding systems are [1]

- the shape and the dimensions of the grounding system,
- the soil resistivity of the ground that surrounds the grounding system,
- the development of soil ionization or not,
- the injection point,
- the waveshape of the injected current.

During the transient state, the impedance of the grounding systems is much greater than in the steady state [2–7]. The cause of this is that during the transient state [2]:

- The reactance of the conductors and the connections is getting greater due to the small duration of the phenomenon. This small duration has as a result high frequency development and therefore the increase of the earth's impedance.
- The reduction of the front time of the injected impulse current leads to the reduction of the effective length of the long earth conductors.
- The skin effect increases the impedance of the earth conductors, due to the high frequency that is dominating during the transient phenomenon.
- The high value of the injected current may dry the soil and it will increase the soil resistivity.

The impulse transient impedance of a grounding system is defined as the ratio of the potential variation of the point, where the current is injected towards the infinite earth to the injected current [1–7]:

$$z(t) = \frac{u(t)}{i(t)}. \tag{1}$$

Due to the fact that the impulse transient impedance is a time varying magnitude, some of its parameters have to be defined. In figure 1 the characteristic points of the $u(t)$ and $i(t)$ curves, which were used for the definition of the parameters of the impulse transient impedance, are presented.

Equations (2)–(5) present the definitions of the impulse transient impedance parameters Z_1, Z_2, Z_3, Z_4 [2]:

$$Z_1 = \max((z(t)) \tag{2}$$

$$Z_2 = \frac{u(t_1)}{i(t_1)} \tag{3}$$

$$Z_3 = \frac{u(t_1)}{i(t_2)} \tag{4}$$

$$Z_4 = \frac{u(t_2)}{i(t_2)}, \tag{5}$$

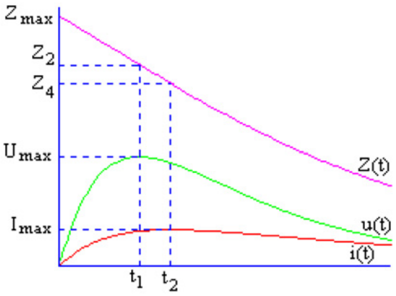

Figure 1. Definition of the parameters of the impulse transient impedance.

where Z_1 is the maximum value of impulse transient impedance ($z(t)$), Z_2 is the ratio of the maximum voltage value to the respective instant current value, Z_3 is the ratio of the maximum voltage value to the maximum current's value and Z_4 is the ratio of the voltage, when the current is maximum, to the maximum current value.

Consequently the following formula is valid:

$$Z_1 > Z_2 > Z_3 > Z_4 > R. \tag{6}$$

It is obvious that the impulse transient impedance is greater than the resistance's value at the steady state (R) that can easily be measured using a ground meter. Consequently, a constructor of grounding systems should not focus on the resistance's value during the steady state, but on the time variation of the impulse transient impedance. The increase of the grounding system's impedance during the transient state is very important, because a great value of the earth resistance at the transient state (for example during lightning injections) may cause malfunctions or even destruction of the installation and of the equipment that the grounding system protects.

In the bibliography there is a plethora of papers on the behaviour of the grounding systems, not only in the transient state, but also in the steady state [2–7]. The majority of them present only a theoretical analysis of the phenomenon, while the transient behaviour of grounding systems, when the current is injected at every point of the grid, has attracted limited attention. The present experimental work makes an effort to fill this gap. Different experiments that have been carried out by other researchers were conducted for current injections only at two points (in the centre and in one corner of the grid) of the scale model grids [7] or in grids with real dimensions [5].

2. Experimental procedure

The purpose of the scale model experiments is the investigation of the variation of the transient resistance of the grounding grids, when the impulse current is injected each time at a different point of the grounding grid. The experimental setup is presented in figure 2. For the production of the impulse current, an impulse current generator is used, with peak value current output in the range of 0.1–25 kA. The output of the impulse generator is applied to the grid and a digital oscilloscope measures the voltage and the current variation on the grid. The voltage and the current's waveform were measured using an ohmic divider embodied in the impulse generator (50 kΩ/50 Ω), a current shunt (1 mΩ, 20 MHz) and an oscilloscope with a bandwidth of 150 MHz and a sampling rate of 200 MS s^{-1}.

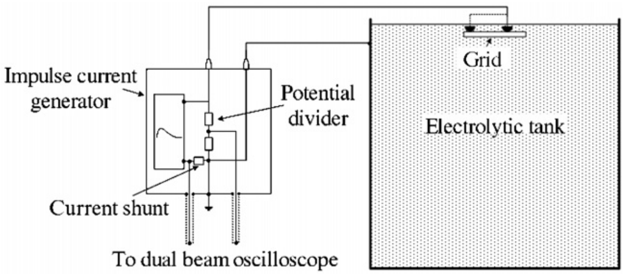

Figure 2. Experimental setup.

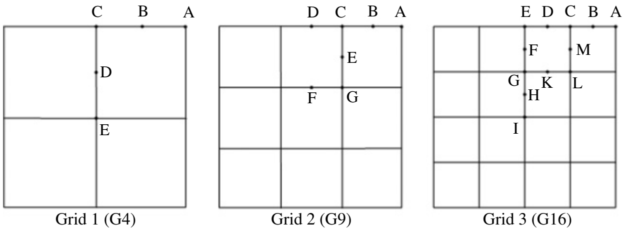

Figure 3. The grids 1, 2 and 3 with 4, 9 and 16 meshes (named G4, G9 and G16 respectively), with the points where the measurements were conducted.

Although the best shape for an electrolytic tank is hemispherical, due to the obvious practical difficulties, cylindrical or orthogonal tanks are more often used [8–10]. The dimensions of the electrolytic tank which has been used for the experiments are 1.5 × 1.5 × 1.0 m^3. The maximum dimension of the grid (the diagonal for a square mesh) must be at least two or three times smaller than the minimum dimension of the tank. For a scale factor 100:1, a variety of grids with outside dimensions of 20 × 20 cm^2 have been modelled and tested. The depth of the tank must not be less than half the side of the tank. Salted tap water is used as an electrolyte, which serves as an adequately conducting medium, representing the homogeneous earth. Change in the salinity causes a change in the liquid resistivity.

The layouts of the grounding systems (figure 3) are tested experimentally under impulse lightning current. The first grounding system is a square grid with four meshes (G4), the second grid has the same outside dimensions and nine meshes (G9), while the third one has the same outside dimensions and 16 meshes (G16). Copper rods of 2.5 mm^2 are used for the construction of the grounding systems. The grid that was used each time was placed in the centre of the full water tank, and at depths of 2 and 4 cm under the water surface. The model grid was hung on nylon fishing lines below the surface of the electrolyte. Hanging provides a horizontal configuration with minimum deformation and bend.

The injection of the current was applied to various points starting from the corner of each grid and going to its internal points. Due to the grids' symmetries, measurements were not conducted at all points, but only at the points that are indicated with capital letters in figure 3. At each measurement point, impulse currents of different peak values were injected. In order to change the peak value of the injected current the

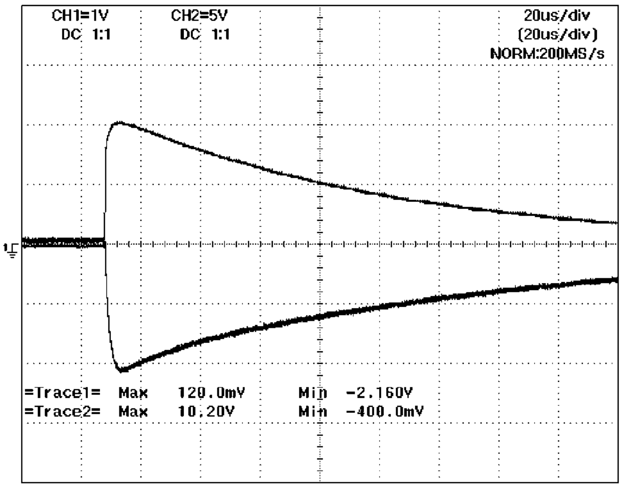

Figure 4. Grid 1 (G4), depth 2 cm, point A, conductivity 2.5 mS cm^{-1}.

charging voltage of the impulse current generator was changed. The rise time of the injected current is 8 μs ± 20% and the duration to half peak is 80 μs ± 20%.

3. Results

The experimental procedure previously described was repeated for each grounding grid of figure 3, injecting impulse current at each chosen point, and for water conductivity values of 2.5–5.0−7.5 mS cm^{-1}. The derived shape of the oscillograph is shown in figure 4. The measurements were also available in digital form. The positive waveform corresponds to the measured voltage, while the negative waveform corresponds to the injected current. The injected current is not negative; nevertheless for a better illustration of the oscillographs, it has been selected to be presented in the negative direction. For every measurement set the average and the deviation of each parameter of the transient impulse impedance (equations (2)–(5)) were calculated. In the case of parameter values outside the level of confidence of 95%, these were removed and the average of the measurements was calculated again.

In figures 5–10 the variation of the average for the parameter values Z_2, Z_3, Z_4 of the impulse impedance for every grid, various depths and representative conductivity values are presented.

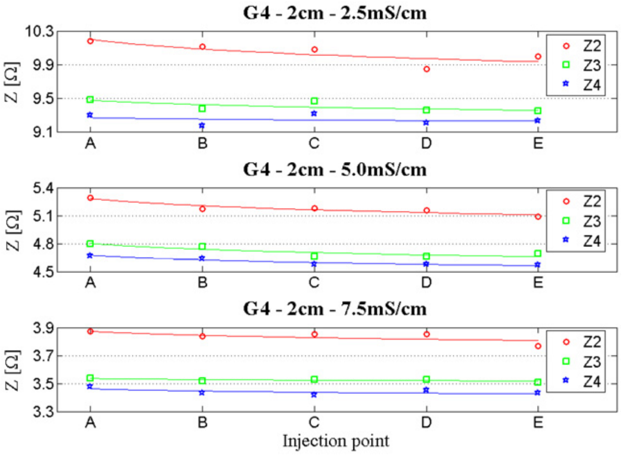

Figure 5. Variation of the parameters Z_2, Z_3, Z_4 of grid 1 (G4), placed at a depth of 2 cm for all grid points and for water conductivities of 2.5–5.0–7.5 mS cm^{-1}.

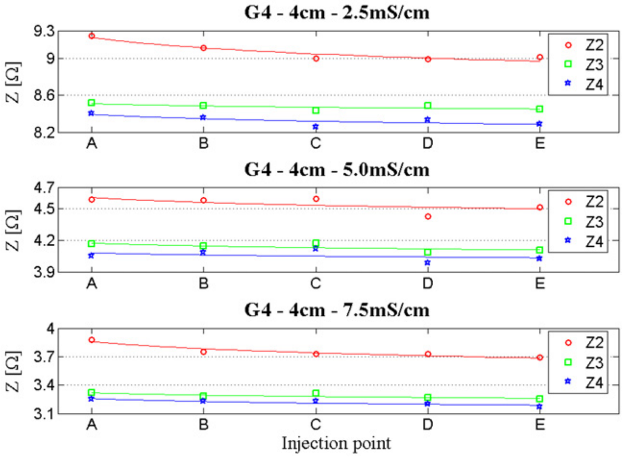

Figure 6. Variation of the parameters Z_2, Z_3, Z_4 of grid 1 (G4), placed at a depth of 4 cm for all grid points and for water conductivities of 2.5–5.0–7.5 mS cm^{-1}.

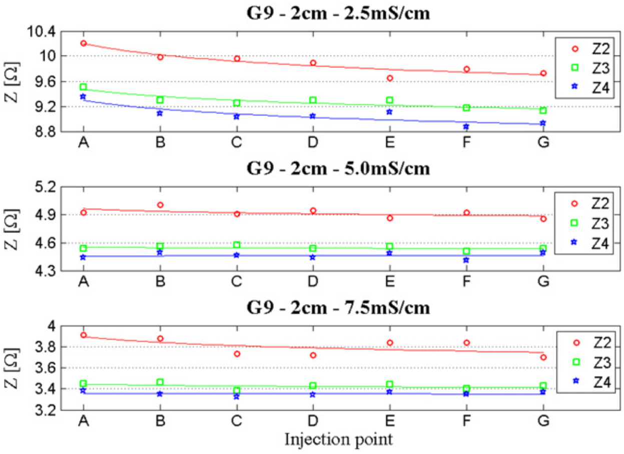

Figure 7. Variation of the parameters Z_2, Z_3, Z_4 of grid 2 (G9), placed at a depth of 2 cm for all grid points and for water conductivities of 2.5–5.0–7.5 mS cm^{-1}.

The statistical processing of the results, presented in figures 5–10, concludes that the mean values of the parameters Z_2, Z_3 and Z_4 for grid G4 are higher than the respective parameters for grid G9, which are sequentially higher than the respective parameters of grid G16. This was expected, since the grids with more squares have smaller resistance, due to the greater length of the conductor. The resistances of the grid and of the tank's water were measured, as these were the path through which the impulse current is led to the earth. Consequently, since the tank's water has higher resistance than the grid, it can be concluded that in the case of grids with more meshes, there are more paths for the current and therefore the total resistance of the grounding system is smaller. The increase in length of the grid's conductors (grid with more meshes) and of the depth where the grounding grid is placed have resulted not only in the decrease of the steady state

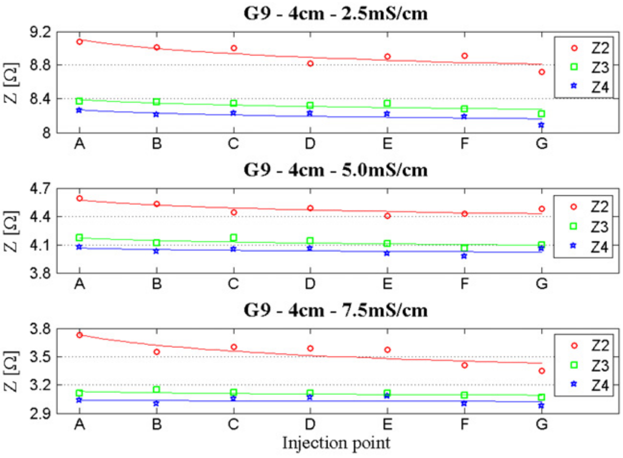

Figure 8. Variation of the parameters Z_2, Z_3, Z_4 of grid 2 (G9), placed at a depth of 4 cm for all grid points and for water conductivities of 2.5–5.0−7.5 mS cm^{-1}.

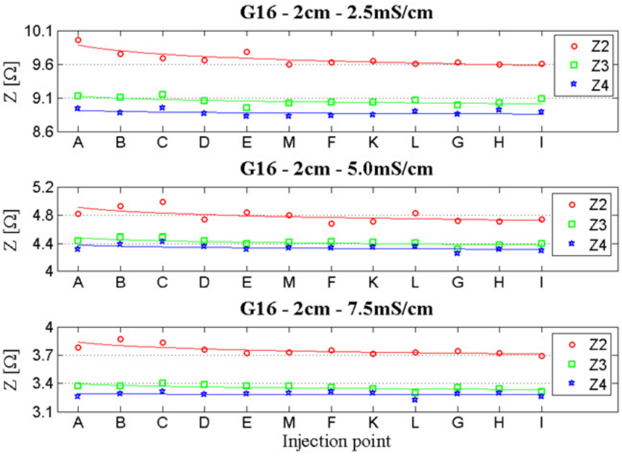

Figure 9. Variation of the parameters Z_2, Z_3, Z_4 of grid 3 (G16), placed at a depth of 2 cm for all grid points and for water conductivities of 2.5–5.0−7.5 mS cm^{-1}.

resistance, but also in the decrease of the transient impedance's parameters.

In figures 5–10 the variation of the parameters of the impulse impedance in relation to the injection point for various grids, depths and conductivities is illustrated. Accordingly, it can be concluded that the mean values of the parameters of the impulse impedance are higher when injection takes place at the external points, in relation to the values that are observed when the injection takes place at the internal points of the grid. This remark is in accordance with the experiments of other researchers [5–7].

Furthermore it is concluded that the shapes of the parameter variations Z_2, Z_3 and Z_4 are similar. Consequently, there is no need to calculate separately all these parameters using an oscilloscope, since the parameter Z_3 can be calculated using peak voltmeters. Plotting the variation of the parameter Z_3, the other parameters can be estimated: the value of the parameter Z_3 ranges about 1–3% higher than the value of Z_4 and the value of the parameter Z_2 ranges about 6–12% higher than the value of Z_4. The value of the parameter Z_2 ranges about 55–100% higher than the value of the resistance in the steady state.

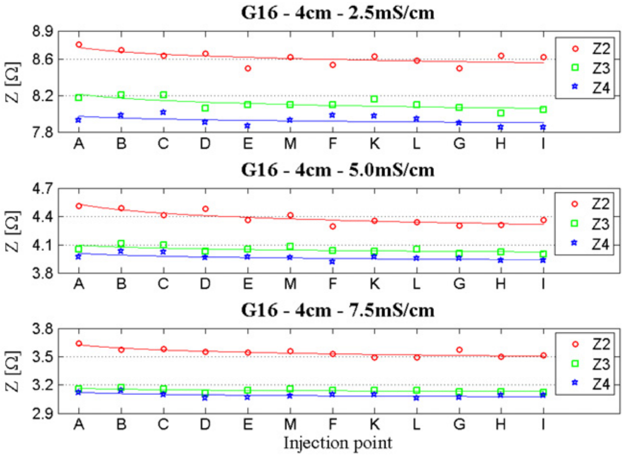

Figure 10. Variation of the parameters Z_2, Z_3, Z_4 of grid 3 (G16), placed at a depth of 4 cm for all grid points and for water conductivities of 2.5–5.0−7.5 mS cm^{-1}.

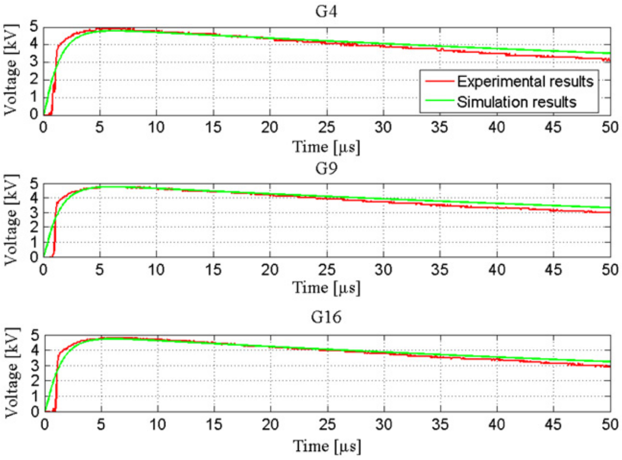

Figure 11. Comparison between experimental results (red line) and simulation results (green line) for grids G4, G9 and G16.

In the past, the author presented a method for the simulation of the transient behaviour of horizontal grids using the software package PSCAD/EMTDC [11]. That mathematical model is characterized by a circuital approach, which is based on the π nominal circuit. Using the same methodology numerical results are presented in figure 11 for two grids (G4 and G9). The aim of these simulations is to verify the applicability of this approach to the behaviour analysis of grounding systems. It is obvious that the simulations results show very good agreement with the experimental results.

4. Conclusions

The improvement and reinforcement of installed grounding systems is a very difficult and usually impossible task. In this paper, the transient behaviour of the grounding grids under impulse lightning currents using scale models in an electrolytic tank is investigated. The variation of the parameters of the impulse impedance in relation to the injection point for various grids, depths and conductivities is presented. These experimental results could help in improving the simulations accuracy. These give the possibility of changing the π nominal circuit of the circuital approach.

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