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Transient behaviour of a horizontal electrode under impulse current

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Abstract: This paper deals with the transient behaviour of a horizontal electrode under impulse current. The contribution of this paper is to verify the applicability of the circuital approach in the behaviour analysis of a horizontal grounding electrode injected by impulse current. The proposed approach can be used as a simple, accurate and useful methodology in the design of a grounding system, which consist of a not long length electrode. Different simulations have been carried out altering the shape of the impulse current, the soil resistivity and the length of the electrode using the PSCAD/EMTDC package. A very good agreement has been ascertained comparing the results (transient impedance of the electrode and the transient voltage) of the suggested method with corresponding results, which are published by other researchers. The authors have carried out a large number of experiments using a high impulse current generator, a resistive voltage divider, an impulse current shunt and a dual beam digital oscilloscope. The relevant experimental results are found to agree favourably with the results of the simulation. Also, the dependence of the peak of transient voltage versus the time to crest and the time to half value of the injected current are presented.

1. Introduction

The grounding system constitutes one of the most important parts of building construction. The grounding systems resistance has an essential influence on the protection of the relevant building. As it is stated in the ANSI/IEEE a safe grounding design provides means to carry electric currents into the earth under normal and fault conditions and assures that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock. Grounding systems can consist of one or more verticals or horizontal ground rods or grids. A system that combines a horizontal grid and a number of vertical ground rods penetrating lower soil layers has several advantages in comparison to a grid alone [1, 2].

The grounding resistance and other characteristics of the grounding system steady state response can be computed directly in the time domain. The analysis of the transient behaviour of a grounding system is simulated usually by a circuital approach [3-11]. This approach may use either a π nominal circuits model [3-5], or a transmission line model with distributed parameters [6-10], or an altered π nominal circuits model [11].

2. Fundamentals

The work reported in this paper refers to the problem of transient analysis of a grounding electrode buried in depth h under injection of a lightning impulse current. In order to validate the behaviour of grounding systems the knowledge of their performance over a wide range of frequencies is required. The basic model is developed through the circuital approach, which models an earth conductor as equivalent π-circuits involving R-L-C-G elements [3, 4].

The resistance R and the self-inductance L are connected in series, while the transverse conductance G and the capacity C are connected in parallel. The most meaningful of the series elements is the self-inductance L, while the resistance R, which represents the losses in the conductor, is usually negligible. The conductance G, which represents the losses to earth, is the most meaningful of the elements in shunt position, while the capacitance C is usually neglected, as its influence is small in comparison to that of the conductance.

The current distribution in a cylindrical conductor, through which direct current flows, is uniform, and the conductor resistance R is given by

$$R = \rho \cdot \frac{l}{\pi \cdot r^2} \qquad (1)$$

where ρ is the resistivity of the material, l is the length and r the radius of the conductor.

The transverse conductance G of the conductor is given by the following equation:

$$G = \frac{2 \cdot \pi}{\rho_s} \cdot \frac{\Delta l}{\ln\left(\frac{l}{r}\right) + \ln\left(\frac{l}{2 \cdot h}\right)} \qquad (2)$$

where ρ_s is the soil resistivity and Δl the length of each one of the elementary parts in which the electrode is divided.

The inductance L of a conductor of length l is given by

$$L = \frac{\mu \cdot \Delta l}{2 \cdot \pi} \cdot \left[\ln\left(\frac{l}{r}\right) + \ln\left(\frac{l}{2 \cdot h}\right) \right] \qquad (3)$$

where μ is the magnetic permittivity of the material.

The capacitance C to earth of each one part of the conductor is given by

$$C = \varepsilon \cdot \rho_s \cdot G \qquad (4)$$

where ε is the permittivity of the soil.

3. Experimental apparatus and test results

The aim of our experiments was the study of the transient behaviour of horizontal electrodes. The investigated electrodes had a length of 2m respectively 4m (s. cases D and E in Table 1, where also the geometric characteristics as well as the soil characteristics are presented; in the same table three other cases (A, B, C) are also presented, they will be discussed in the next paragraphs of this parer).

Case	A	B	C	D	E
Soil resistivity ρ [Ωm]	70	100	1000	38	38
Dielectric constant ε_r	15	36	9	40	40
Length of the electrode ℓ [m]	15	100	100	2	4
Depth h [m]	0.6	0.6	0.6	0.6	0.6
Radius of the electrode r [mm]	12	2.5	2.5	9	9

Table 1: Characteristics of the electrodes and of the soil.

The test arrangement is shown in Fig. 1. It includes a high impulse current generator with maximum stored energy of 1.5kWs. It generates impulse currents of the waveform 8/20 μs and with a peak value up to 25kA. The impulse voltage is measured by means of a resistive voltage divider (50kΩ/50Ω). The injected impulse current is measured by an impulse current shunt (1.0mΩ). The impulse voltage divider and the current shunt are built in the impulse generator cover. The measuring instrument is a dual beam digital oscilloscope with a sample rate of 200MS/s. The time between successive impulse applications is at least 1 min.

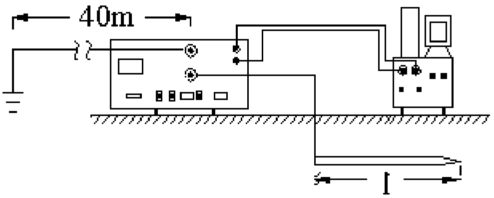

Figure 1: Experimental set-up.

The investigated waveforms are shown in Fig. 2 and Fig. 3 for electrodes with length 2m and 4m, respectively. The injected current waveform is 8/70 μs ±20%. The waveform of voltage (between the point where the current is injected and the ideal earth), which has been recorded, is 7/70 μs ±20%. It is also observed that the transient impedance is converged very fast (less than 4 μs) in the value of the impedance of the steady state, which is decreased to 70% when the length of the electrode is doubled (from 19Ω is decreased to 12Ω).

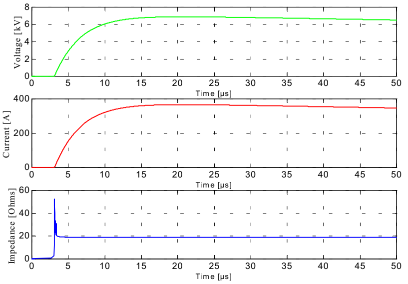

Figure 2: Injected current, transient voltage and transient impedance vs. time for the horizontal electrode D.

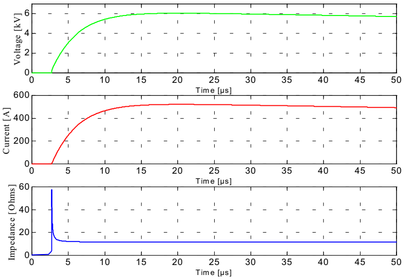

Figure 3: Injected current, transient voltage and transient impedance vs. time for the horizontal electrode E.

4. Simulation Results

The authors have examined five different cases of electrodes, to make possible the comparison of the results. The characteristics of the investigated electrodes, which are made of copper, and of the soil, where the electrodes are buried, are shown in Table 1. Altering the shape of the impulse current, the soil resistivity and the length of the electrode, the change of voltage and grounding impedance in the time domain are examined.

The experimental [12] and the simulation [8] results for the electrode A (Table 1) are shown in Fig. 4.

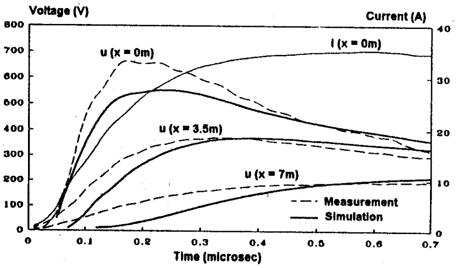

Figure 4: Experimental and simulation results of the horizontal electrode A [8, 12].

The simulation results of our suggested method are presented in Fig. 5. In our EMTDC results the voltage waveforms (for different distances from the begin of the electrode; ⊟, respectively △, respectively ▽: at the injection point, respectively at a distance of 3.5m, respectively 7m from it) have very good agreement with the experimental ones [12]. In Fig. 6 are compared our experimental results with the simulation results for the electrode E of the Table 1; the comparison ascertained a very good agreement between them.

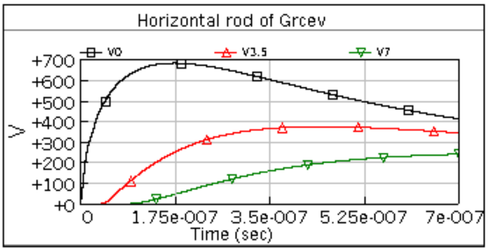

Figure 5: Simulation results of horizontal electrode A.

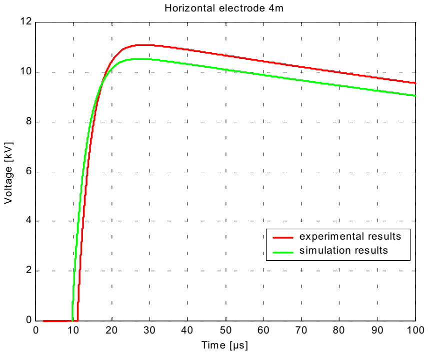

Figure 6: Experimental and simulation results of voltage vs. time for horizontal electrode E.

It is obvious that the simulation and experimental results are in a very good agreement, while, moreover, the methodology used for the PSCAD/EMTDC simulation is clearly simpler than that suggested in other papers [6-11].

Measurements of the lightning current, which have taken place at the NASA Kennedy Space Center, Florida and at Fort McClellan, Alabama by Thottappillil et all [13], have proved that usual lightning currents can be simulated by waveforms according to the double exponential form:

$$i(t)=I_o\cdot\left(e^{-a\cdot t}-e^{-b\cdot t}\right) \qquad (9)$$

Usually recorded lightning currents have the values of the parameters *a* and *b* (s. equation (9)), presented in Table 2.

Case	a $[s^{-1}]$	b $[s^{-1}]$	T_{crest} [μs]	T_{half} [μs]
1	16667	100000000	0.1	43
2	16667	25000000	0.3	43
3	16667	10000000	0.6	43
4	16667	2857143	1.8	43
5	16667	2127660	2.4	43
6	16667	1538462	3.0	43
7	80000	3703704	1.2	10
8	37037	4545455	1.2	20
9	25000	5000000	1.2	29
10	16667	5000000	1.2	43
11	11806	6079027	1.2	60
12	7018	6211180	1.2	100

Table 2: Parameters of injected currents.

The variation of the peak value of the transient voltage for cases B and C of Table 1 versus the time to crest of the injected current for fixed time to half value (equal to 43 μs) is shown in Fig. 7. It is observed that the decrease of the time to crest of the injected current increases the peak value of the transient voltage. In cases B and C of Table 1 the value of the soil resistivity is varied. The value of the resistance and the value of the voltage in the steady state increase linearly with the soil resistivity. On the contrary, in the transient state, it is observed that, when the soil resistivity becomes ten times (from 100 Ωm to 1000 Ωm) higher, then the peak value of voltage is increasing two to four times (Fig. 7).

The peak value of the transient voltage for cases D and E of Table 1 versus the time to crest of the injected current is shown in Fig. 8. In cases D and E of Table 1 the length of the electrode is varied. It is obvious that, as higher the length of the electrode, as lower the peak value of the voltage. When the length of the electrode is doubled, the peak voltage is decreased by 35% and this percentage decreases as the time to crest decreases.

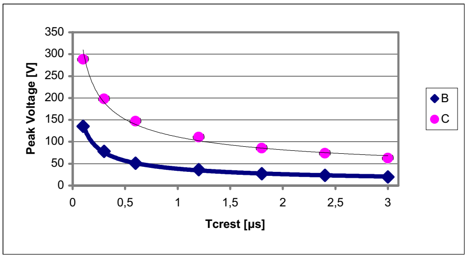

Figure 7: The peak value of voltage versus the time to crest of the injected current in cases B and C.

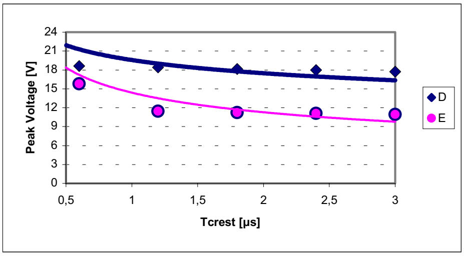

Figure 8: The peak value of voltage versus the time to crest of the injected current in cases D and E.

The variation of the peak value of the transient voltage for cases B and C of Table 1 versus the time to half value of the injected current for fixed time to crest (equal to 1.2 μs) is shown in Fig. 9. It is observed that the increase of the time to half value of the injected current increases the peak value of the voltage. Also, the increase of the soil resistivity has the same influence on the peak voltage, independently of the time to half value.

The variation of the peak value of the transient voltage for cases D and E of Table 1 versus the time to half value of the injected current for fixed time to crest (equal to 1.2 μs) is shown in Fig. 10. In these cases it is also obvious that the increase of the time to half value increases the peak value of the voltage. Furthermore, when the length of the electrode is doubled, then the peak voltage is decreased approximately to 65%.

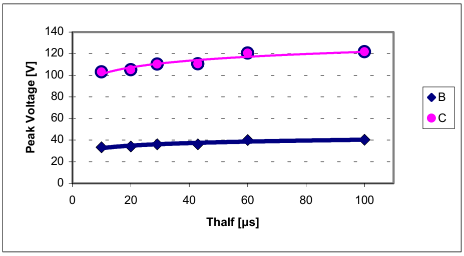

Figure 9: The peak value of voltage versus the time to half value of the injected current in cases B and C.

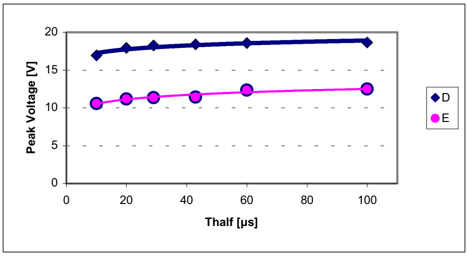

Figure 10: The peak value of voltage versus the time to half value of the injected current in cases D and E.

5. Conclusions

The proposed approach can be used as a simple, accurate and useful methodology in the design of a grounding system. A very good agreement has been ascertained, by comparing the results of the suggested method with corresponding results of other researchers.

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