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Analysis of transient behaviour of a Concentrated Cylindrical Vertical Grounding Rod by Magnetodynamic Finite Element Modeling

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Abstract

This paper deals with the transient analysis of a vertical cylindrical grounding rod by means of the finite element technique. Capacitive effects are neglected, and then the magnetodynamic problem is modeled by a magnetic-field formulation. This technique permits to analyze the electrical potential, the impulse impedance and the effective length of a cylindrical vertical rod. The advantage of this technique is to take easily into account the real properties of the soil (with several layers of different resistivities) and the rod. To reduce the DC resistance of a rod, this can be coated with a high conductive material. The influence of this configuration on transient behaviour of the rod will be highlighted in this paper. The results are validated by comparison with an analytical method.

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INTRODUCTION

During the last years, several papers have been published concerning the transient behaviour of grounding systems [Grcev, 2009; Liu et al., 2001; Grcev et al., 1999; Gupta et al., 1978; Llovera et al., 1960]. Grcev [2009] proposed a full-wave analysis method that is based on the rigorous electromagnetic field theory. It is considered as most accurate in comparison to the methods based on transmission line methods [Liu et al., 2001] or circuit theory approaches [Grcev et al., 2003]. We propose the magnetodynamic finite element modeling based on Maxwell equations with the assumption of quasi-static approximation. The condition of validity of this assumption was given by Olsen in [1996]. We do not consider the effect of displacement current; i.e. the capacity of the rod is then neglected since this has little influence to the rod potential as shown by Liu [2001]. The results are compared with those given by Grcev [2009]. The advantage of the finite element method is to consider the properties of all regions, for example the soil with several layers of different resistivities can be easily analyzed.

To reduce the DC resistance of a rod, this can be coated with a high conductive material such as bentonite. In this paper we propose the powdered charcoal that has high conductivity as shown by Cohen-Ofri II [2006]. The finite element method presented here allows evaluating the transient performance of such a rod.

MAGNETODYNAMIC FORMULATION

The Maxwell equations and constitutive laws characterizing the magnetodynamic problem defined in a domain Ω delimited by the boundary $\Gamma = \Gamma_h + \Gamma_b + \Gamma_j$ are, in quasi-static approximation [Dular et al., 2000]:

$$\mathrm{curl}\, \boldsymbol{h} = \boldsymbol{j} \;,\; \mathrm{curl}\, \boldsymbol{e} = -\partial_t \boldsymbol{b} \;,\; \mathrm{div}\, \boldsymbol{b} = 0 \qquad (1\ \text{a-c}),$$

$$\boldsymbol{b} = \sigma \boldsymbol{j} \;, \quad \boldsymbol{b} = \mu \boldsymbol{h} \qquad \text{(2a-b)}$$

with boundary conditions

$$\boldsymbol{n} \times \boldsymbol{h}|_{\Gamma_h} = 0 \quad \boldsymbol{n} \cdot \boldsymbol{b}|_{\Gamma_b} = 0 \quad \boldsymbol{n} \cdot \boldsymbol{j}|_{\Gamma_j} = 0 \quad \text{(3 a-c)}$$

Where $\boldsymbol{h}$ is the magnetic field, $\boldsymbol{j}$ is the electric current density, $\boldsymbol{e}$ is the electric field, $\boldsymbol{b}$ is the magnetic induction, σ is the conductivity, μ is the magnetic permeability and n is the unit normal exterior to Ω .

Given that there is no current flowing in the air, we can have a scalar potential ϕ such as

$$\boldsymbol{h} = -\,\mathbf{grad}\ \phi \qquad (4)$$

The magnetic-field formulation obtained from the weak formulation of Faraday's law (1b) is [Dular et al., 2000]:

$$\partial_t \left(\mu \boldsymbol{h}, \boldsymbol{h}'\right)_\Omega + \left(\sigma^{-1} \text{curl}\, \boldsymbol{h}, \text{curl}\, \boldsymbol{h}'\right)_\Omega + \left\langle \boldsymbol{n} \times \boldsymbol{e}, \boldsymbol{h}'\right\rangle_{\Gamma_e} = 0 \qquad (5)$$

Where $(\ ,\ )$ is the volume integral, $\langle\ ,\ \rangle$ is the surface integral of the product of their arguments and, $\boldsymbol{h}'$ is the test magnetic field function.

FINITE ELEMENT MODELLING OF A CYLINDRICAL VERTICAL GROUNDING ROD

The model of a vertical cylindrical grounding rod embedded in a soil is shown in Figure I. Taking advantage of the symmetry, a hemispherical sector is considered. The injected current $\boldsymbol{I}$ is represented by the analytic expression of a lightning (Figure II).

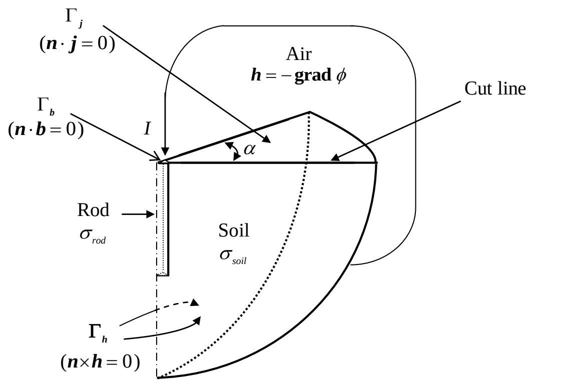

Figure I. **Hemispherical sector model of the rod and the soil**

VALIDATION OF THE MODEL

Considering a vertical cylindrical rod of copper, embedded in a homogenous soil with a resistivity of 100 Ω.m, we compute the potential at the current injection point of the rod; Figure III shows the results. The return stroke lightning current wave is used as in analytical formula (1), based on Berger experiments [1975] shown in Figure II. These results agree with those given by Grcev in [2009].

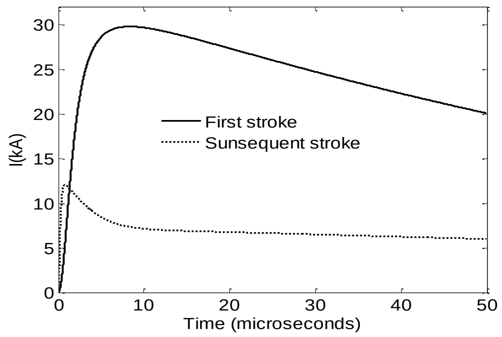

Figure II. **Lightning current waves based on Berger experiments**

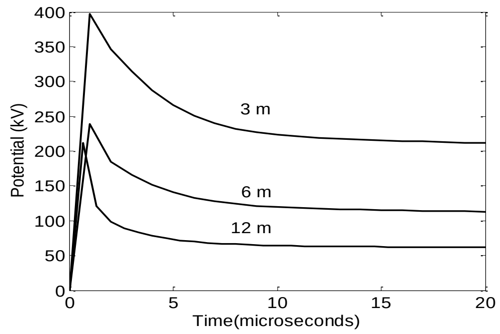

Figure III. **Potential at injection point, cylindrical vertical rod, r = 7 mm**

APPLICATION EXAMPLE

Analysis of a rod surrounded by a high conductive material

Figure V shows a vertical rod surrounded by a material of high conductivity (powdered charcoal is used here). At power frequencies (50 and 60 Hz), this allows to reduce the rod resistance.

It is important to know the transient behaviour of such a rod.

Fagan and al. [1970] proposed an analytical formula for computing the resistance of such a rod given by:

$$R_m = \frac{1}{2\pi l} \left\{ \rho_m \left[\ln\left(\frac{r_m}{r}\right) \right] + \rho \left[\ln\left(\frac{4l}{r_m}\right) - 1 \right] \right\} \qquad (6)$$

Where ρ_m is the resistivity of the high conductivity material, ρ is the soil resistivity, r_m is the radius of the material and r is the radius of the rod. This formula gives no physical (negative) values of resistance for high values of r_m as shown in Figure IV. To overcome this problem, we used electrokinetic finite element formulation to determinate the DC resistance. Figure IV shows the resistance calculated with the analytical formula (6) and that computed by electrokinetic finite element formulation, for the cylindrical copper vertical rod (diameter: 1.25 cm, length: 1 m) buried in a 1000 Ω.m soil. It is shown clearly that the relative error between the two results increases with the increase of r_m .

Example

Consider a vertical rod embedded in the soil with 4 layers of different resistivities, surrounded by the powdered charcoal such as given in the Figure V. The Figure VI shows the potential at injection point ratio, the impulse efficiency of the rod without and with the powered charcoal around.

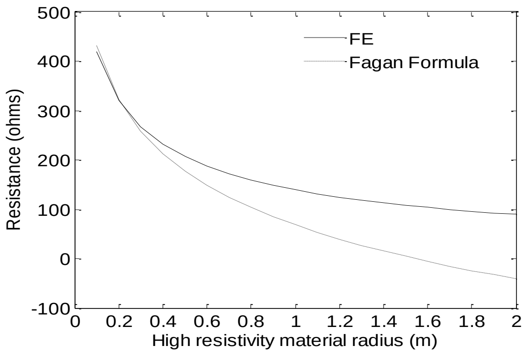

Figure IV. **Resistance of a rod surrounded by a high conductivity material: analytical and finite element results**

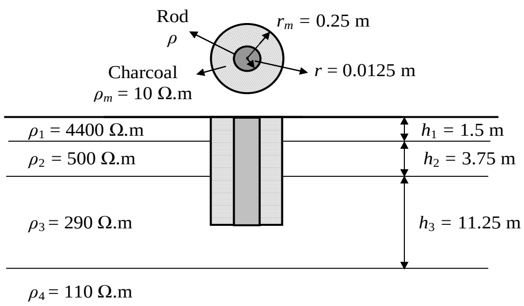

Figure V. **Vertical grounding rod surrounded by a high conductivity material**

The impulse efficiency (IE) of a rod is the ratio between its maximum transient impedance and low frequency resistance.

The results show that adding a layer of charcoal around the rod improves the transient behaviour of the rod. The potential can then be divided by a factor between 1.2 to 3, depending on the rod length. This factor decreases with the rod length and is independent of lightning wave shape. The impulse efficiency increases. The effective length of the rod decreases (20 m to 16 m for the first stroke and 6 m to 5 m for the return stroke).

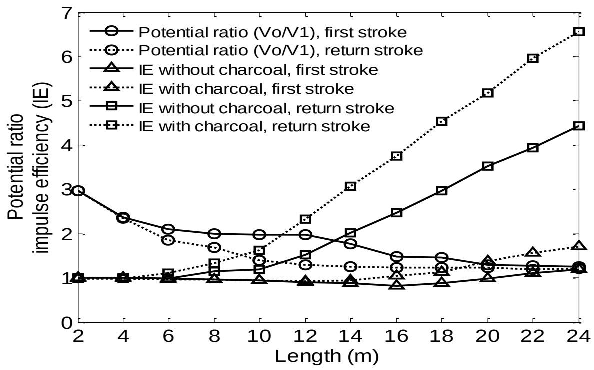

Figure VI. **Potential ratio, impulse efficiency (Vo is the potential without charcoal and V1 is the potential with charcoal)**

CONCLUSION

The transient analysis of a cylindrical vertical rod by the magnetodynamic finite element method has been shown. This technique permits to analyze the electrical potential, the impulse impedance and the effective length of a cylindrical vertical rod. The finite element method has an advantage to take into account the real properties of all areas considered. The comparison of the results of potential at injection point with the full-wave analysis method that is based on the rigorous electromagnetic field theory has permitted to validate the model. The transient analysis of a vertical road embedded in the soil with 4 layers of different conductivities permits to show that addition of some material with high conductivity around the rod improves its transient behaviour by reducing the potential by a factor between 1.2 to 3. The effective length is also reduced but more for the first stroke.

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