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Transient analysis of a buried conductor using partial element equivalent circuit method

Abstract. *This paper presents transient analysis of a horizontal buried conductor performed by applying the Partial Element Equivalent Circuit (PEEC) method. A fast rising pulse is injected by a current source at one end of a perfect conductor placed in a finitely conductive ground. The presence of ground/air boundary surface is taken into account by implementing the image theory. The current distribution along the conductor is calculated in the frequency domain, while the time shape of the pulse is reconstructed using Inverse (Fast) Fourier Transform (IFFT). The developed technique is verified by comparison with results calculated with the Numerical Electromagnetic Code 4 (NEC4) solver and shows satisfactory agreement.*

Streszczenie. *W artykule zaprezentowano analizę stanu przejściowego w poziomo zakopanym przewodzie przez zastosowanie metody obwodu zastępczego. Szybko narastający impuls aplikowany jest poprzez źródło prądowe na końcu przewodnika umieszczonego w gruncie o skończonej przewodności. Obecność granicy zienia/powietrze uwzględnina została poprzez wykorzstanie metody odbić. Rozkład prądu w przewodnikuobliczany jest w obszarze częstotliwościowym, podczas gdy czasowy kształt impulsu jest rekonstruowany poprzez metodę odwrotnel szybkiej transformaty Fouriera (IFFT) Rozwijana technika została zweryfikowana przez porównanie wyników obliczeń uzyskanych przez oprogramowanie CODE4 Zgodność została osiągnięta w stopniu zadowalającym. (**Analiza stanu przejściowego zakopanego przewodnika z wykorzystaniem metody obwodu zastępczego)**.*

Keywords: transient analysis, PEEC, current distribution.
Słowa kluczowe: amaliza stanu przejściowego, obwód zastępczy, rozkład prądu.

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Introduction

Lightning discharges often cause disturbances in grounding systems, producing overvoltages and consequently, equipment failure. Horizontal grounding electrodes might exhibit inductive behaviour at high frequencies (HF), which might weaken their lightning-protection capabilities. Therefore, it is of importance to have knowledge of the response of grounding systems to fast rising current pulses. In this paper the transient response of a buried horizontal conductor is determined using the partial element equivalent circuit (PEEC) method [1]. This method transforms electromagnetic problems into electric circuit theory problems by creating a heterogeneous mixed circuit from a full-wave solution of the Maxwell's equations. The equivalent circuit created by PEEC contains a series of self-partial and mutual-partial inductances, shunt capacitances (potential coefficients) and current controlled current sources attached to each node that take into account the electromagnetic properties of the system, as well as coupling and propagation effects. The resulting circuit from the PEEC model can be analyzed using widely spread SPICElike solvers. The circuit based modeling has the advantage of simple inclusion of additional circuit elements when using the PEEC method with commercial circuit simulation software. Another advantage of the PEEC method is the possibility to implement the same circuit model for both time- and frequency- domain analysis.

Transient analysis of the current along the buried conductor

In this section the Partial Element Equivalent Circuit (PEEC) method is applied on a horizontal perfect conductor excited by a pulse current source, buried at depth d in finitely conductive ground with specific conductivity σ_1 and permittivity ε_1. The source current pulse is chosen to represent a most typical lightning strike current shape: a double – exponential fast varying pulse with peak value 1 kA [2], given by the equation

$$i(t) = I(e^{-\alpha t} - e^{-\beta t}) \tag{1}$$

where: $I=1.0167$ kA, $\alpha=0.0142$ μs^{-1} and $\beta=5.073$ μs^{-1}. The source current pulse defined by Eq. (1) is presented in Fig. 1a.

The geometry and segmentation of the buried conductor, the location and the time shape of the source are presented in Fig. 1a. and 1b., respectively.

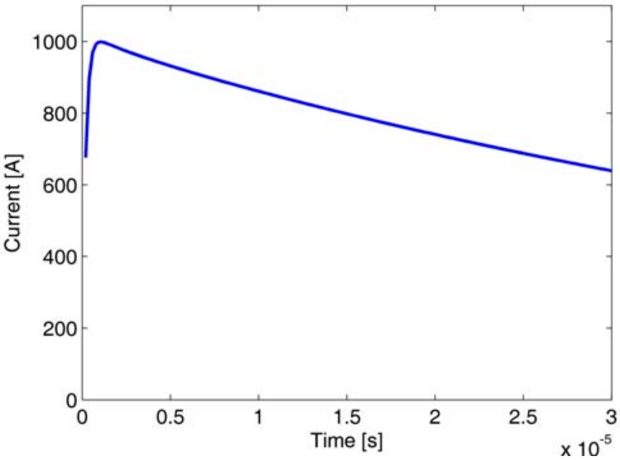

Fig.1a. The fast rising source current pulse

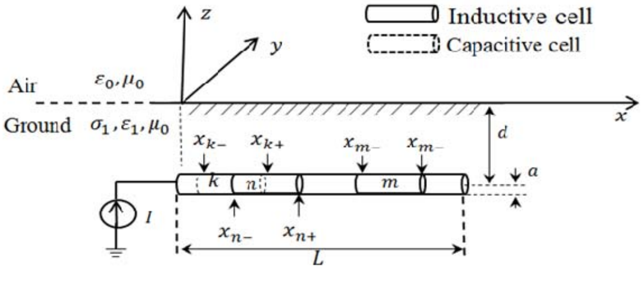

Fig.1b. The perfect conductor buried in finitely conductive ground

The analysis in frequency domain starts with the zero tangential electric field on the surface of the perfect conductor:

$$E_z^t = E_z^i + E_z^s = 0 \tag{2}$$

where: E_z^i is an incident electric field and E_z^s is the scattered electric field. For the case of zero incident field, the scattered electric field equals zero, which leads to the following equation:

$$\frac{\partial\varphi}{\partial z} = -j\omega A_z \tag{3}$$

where: A_z is the magnetic vector potential and φ is the electric scalar potential at the point of interest. The presence of air half space is treated by implementation of the quasi-static image theory, which leads to including the reflection coefficient [2]:

$$R = \frac{\underline{\varepsilon}_1 - \varepsilon_0}{\underline{\varepsilon}_1 + \varepsilon_0} \tag{4}$$

The partial inductances of the equivalent circuit, L_{mn}, are obtained by integrating Eq. (3) along the segment of interest

$$L_{mn} = -\frac{\mu}{4\pi}\int_{z_{m-}}^{z_{m+}}\int_{z_{n-}}^{z_{n+}} g(z,z')dz'dz \tag{5}$$

The general shape of the potential coefficients, P_{jk}, is obtained using the relation between the potential difference along the segment of interest and the charge of the source segment

$$P_{jk} = \frac{1}{4\pi\underline{\varepsilon} l_k}\cdot R\cdot\int_{z'_{k-}}^{z'_{k+}} g(z_j,z')dz' \tag{6}$$

where $g(z,z')$ is the Green's function for the unbounded conductive medium

$$g(z,z') = \frac{e^{-\gamma r}}{r} \tag{7}$$

In Eq. (7), r is the distance between the segment of interest and the source segment, while γ is the propagation constant of the conductive medium

$$r = \sqrt{a^2 + (z-z')^2}\quad,\qquad \gamma = \sqrt{-\omega^2\underline{\varepsilon}\mu} \tag{8}$$

It is visible from the shape of the extracted equivalent circuit elements that coupling between segments and propagation effects are taken into account. Once the equivalent circuit has been synthesized using the determined partial elements, the unknown segment currents are determined implementing the modified nodal approach theory [5].

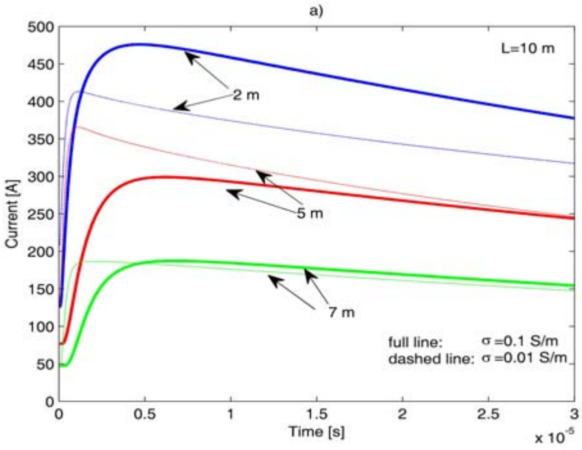

Fig.2a. Obtained time shapes of the current at different locations along a 10 m conductor

Numerical results

Parametric transient analysis of the current and voltage at different locations of the conductor was performed using inverse Fourier transform (IFFT). The obtained time shapes of the current pulse and the voltage response at 2, 5 and 7 m distance along a conductor buried in imperfect ground at depth 0.4 m were investigated for different values of soil conductivity. The obtained values for the current along a perfect conductor with 10 m and 100 m length are presented in Fig. 2a and 2b, respectively. Figures 3a and 3b. present the time shape of the voltage at different locations of the conductor with 10 m and 100 m length, respectively

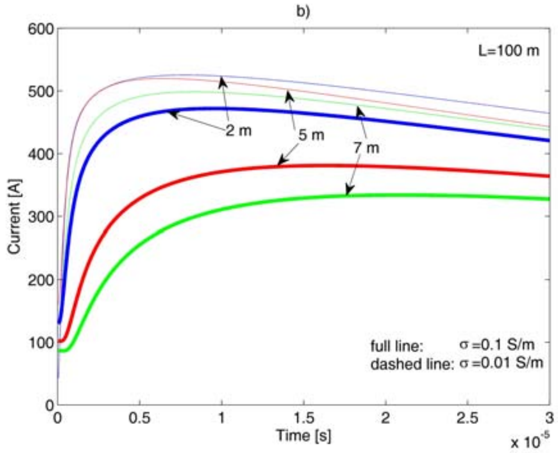

Fig.2b. Obtained time shapes of the current at different locations along a 100 m conductor

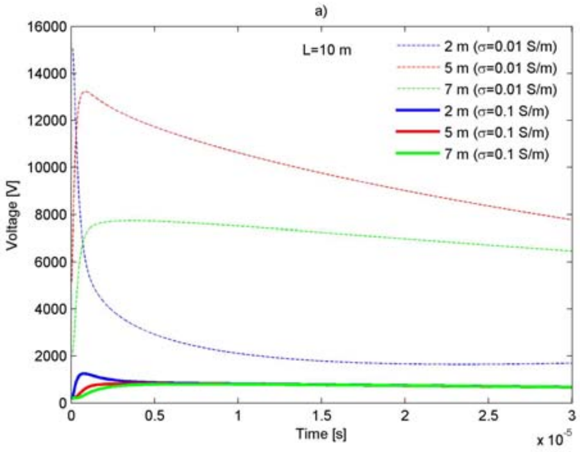

Fig.3a. Obtained time shapes of the voltage at different locations along a 10 m conductor

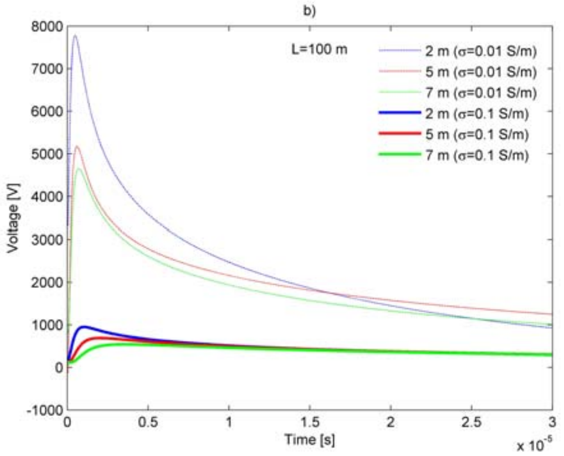

Fig.3b. Obtained time shapes of the voltage at different locations along a 100 m conductor

The validation was performed by comparison of the values for the current obtained by implementation of the PEEC method with results obtained with the well known NEC4 solver [6] for the following case: a 10 m centre-fed dipole buried in imperfect ground at depth 0.4 m. The verification comparison of results is presented for several frequencies in Fig.4

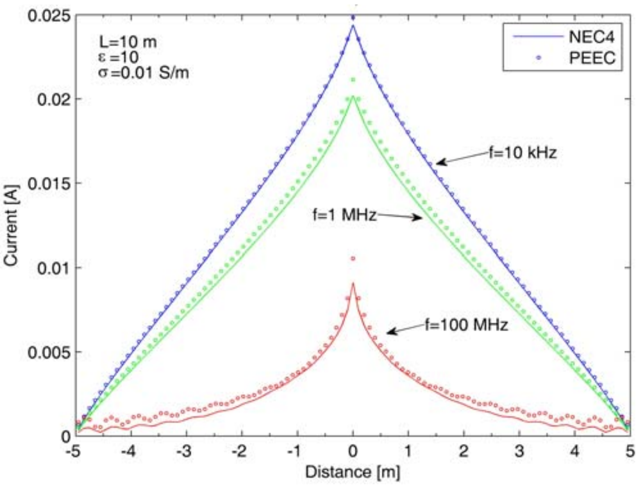

Fig.4. Validation results

Previously, this method was successfully validated by the authors [4] for usage in a homogeneous medium by comparison with values for the current obtained by rigorous MoM calculations [3].

Conclusions

In this paper the Partial Element Equivalent Method was applied to perform transient parametric analysis of the current distribution along a perfect conductor buried in imperfect ground. The conductor was excited by a double-exponential pulse current source, representing the current of a lightning strike. Coupling between segments and propagation effects were taken into account by the equivalent circuit elements. The presence of air half space was included by implementation of the quasi-static image theory, i.e. the reflection coefficient. Parametric analysis of the time shape of the current pulse at different locations was performed using inverse Fourier transform (IFFT). The verification process was performed by comparing the obtained results with ones calculated by the well known NEC4 solver and show excellent agreement. Further research on this topic would include analysis of transient responses of existing grounding systems.

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