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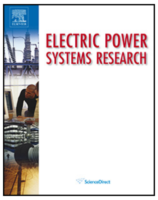

Computation of the electric field in the vicinity of overhead power line towers

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ABSTRACT

There are many numerical models for computing extremely low-frequency electric and magnetic fields of high-voltage substations and power lines. More accurate computation results can be obtained using 3D algorithms. In this paper, a 3D quasistatic model for computation of the scalar electric potential and electric field intensity distribution of overhead power lines is presented. Phase conductors, shield wires and towers of overhead power lines are modelled using thin-wire cylindrical segments of active and passive conductors and using subparametric spatial 2D finite elements. Self and mutual coefficients of these components are numerically computed using an originally developed advanced double 2D numerical integration. Thereafter, they are included in the system of linear equations for computation of the charge density distribution. Special attention is given to examining the influence of the overhead power line towers on the electric field intensity distribution in their close vicinity. Therefore, a computer program for detailed segmentation of typical steel lattice towers of various types is developed. The accuracy of the presented model is verified by comparing the obtained results with other computed and measured published results.

1. Introduction

There is a certain amount of controversy about the possible adverse health effects produced by extremely low-frequency (ELF) electric and magnetic fields in the vicinity of high-voltage substations and overhead power lines [1–4]. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has assessed the available knowledge and published in 2010 guidelines for limiting exposure to time-varying electric and magnetic fields [5]. According to these guidelines, reference levels for 50 Hz electric field intensity are 10 kV/m for occupational exposure and 5 kV/m for general public exposure.

In numerical models for computing ELF electric and magnetic fields, the problem can be considered as quasistatic [6–8]. Quasistatic fields vary slowly with time; therefore, attenuation is equal to zero, whereas the phase shift of these fields can be neglected without a loss of accuracy. Hence, electric and magnetic fields may be computed separately.

In general, numerical algorithms for computing electric and magnetic fields in electric power substations are 3D algorithms [9–14]. However, most numerical algorithms for computing overhead power line electric and magnetic fields are two-dimensional (2D) [15–17]. In these algorithms, overhead power line conductors satisfy a thin-wire approximation and are treated as infinite line sources positioned at a constant distance from the Earth's surface. The number of line sources equals the number of overhead power line conductors. However, in a certain number of real cases, 2D algorithms cannot be applied and must be substituted by more sophisticated 3D algorithms. In 3D algorithms [18–22], the sag of power line conductors can be taken into account. Hence, by using 3D algorithms, it is possible to obtain more accurate computation results of power frequency electric and magnetic fields at any point under complex configurations of overhead power lines.

In this paper, a 3D quasistatic numerical model for computation of the electric field produced by overhead power lines is presented. Overhead power line span conductors are approximated by a set of straight thin-wire cylindrical segments, and time-harmonic current that flows along the conductor axis is approximated by a constant value. In order to show the maximum values of the electric field, most researchers have presented their computations and measurements under the midspan of the overhead power lines. The proximity effect of nearby objects is thereby often ignored. As is well-known [23–26], the electric field is strongly perturbed by the presence of objects such as towers, trees, fences etc. Here, in order to determine the influence of the overhead power line towers to the electric field distribution in their close vicinity, special attention is

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given to segmentation of typical steel lattice towers. Therefore, a one-circuit “Y” tower is approximated using thin-wire cylindrical segments of passive conductors and also using subparametric spatial 2D finite elements. The obtained results of the scalar electric potential and electric field intensity distribution in the close vicinity of the tower are shown. Moreover, in order to verify the accuracy of the presented model, these results are compared with computed and measured results available in the literature. The model presented herein is only a part of a wider time-harmonic quasistatic electromagnetic model for computing electric and magnetic fields of overhead power lines and substations [22]. The foundation of the developed method is the application of the finite element technique (FET) to an integral equation formulation in the frequency domain.

2. System of linear equations for computation of the charge density distribution

Components of the quasistatic electromagnetic model for computation of ELF overhead power lines electric field are thin-wire cylindrical segments of active and passive conductors and subparametric spatial 2D finite elements. Phase conductors, shield wires and towers of overhead power lines are modelled using these components. Furthermore, buried cable line phase conductors and other high-voltage apparatus with complex geometry in the substation can be taken into account using these components.

In this paper, a two-layer medium is observed, in which the first layer is air and the second layer is homogeneous earth. Air is characterised by vacuum permittivity ε_0 and permeability μ_0, whereas earth is characterised by relative permittivity ε_r, permeability μ_0 and electrical conductivity κ.

Using the well-known Galerkin–Bubnov method, which is a special case of weighted residual method, a symmetric system of linear equations for computation of charge density distribution can be obtained using the following expressions:

$$\int_{\Gamma_i} (\bar{\varphi} - \bar{\Phi}_i^s) \cdot d\ell_i = 0; \quad i = 1, \ldots, NS \tag{1}$$

$$\iint_{S_i} (\bar{\varphi} - \bar{\Phi}_i^p) \cdot N_i^p \cdot dS_i = 0; \quad i = 1, \ldots, NP; \quad p = 1, \ldots, NC_i \tag{2}$$

where $\bar{\varphi}$ is the phasor of the computed value of the scalar electric potential, $\bar{\Phi}_i^s$ is the phasor of the prescribed potential of the ith cylindrical conductor segment that is assumed to be constant, $\bar{\Phi}_i^p$ is the phasor of the prescribed potential on the ith spatial 2D finite element that is assumed to be constant, N_i^p is the shape function joined to the pth local node of the ith spatial 2D finite element, Γ_i is the integration path positioned along the ith cylindrical conductor segment axis, S_i is the surface of the ith spatial 2D finite element, NS is the total number of cylindrical conductor segments, NP is the total number of spatial 2D finite elements, and NC_i is the total number of local nodes of the ith spatial 2D finite element.

Continuity of surface charge density at the spatial 2D finite element boundaries is not required. Consequently, local nodes of different spatial 2D finite elements cannot be joined to the same global node. For each subparametric spatial 2D finite element, global coordinates of local nodes for geometry mapping are input data. In such a way, a spatial 2D finite element mesh is defined. According to the usual procedure, using a nodal connectivity matrix, each spatial 2D finite element local node is shown to correspond to some global node number.

According to Eqs. (1) and (2), the following system of linear equations, written in matrix form, can be obtained:

$$\begin{bmatrix} [\overline{PSS}] & [\overline{PSC}] \\ [\overline{PCS}] & [\overline{PCC}] \end{bmatrix} \cdot \begin{Bmatrix} \{\bar{\lambda}\} \\ \{\bar{\sigma}\} \end{Bmatrix} = \begin{Bmatrix} \{\Psi^s\} \\ \{\Psi^p\} \end{Bmatrix} \tag{3}$$

where $[\overline{PSS}]$ is the matrix of the self and mutual coefficients joined to the cylindrical conductor segments, $[\overline{PCC}]$ is the matrix of the self and mutual coefficients joined to the nodes of the spatial 2D finite elements, $[\overline{PSC}] \equiv [\overline{PCS}]$ is the matrix of the mutual coefficients of the cylindrical conductor segments and nodes of the spatial 2D finite elements, $\{\bar{\lambda}\}$ is the cylindrical conductor segments linear charge density vector, and $\{\bar{\sigma}\}$ is the global surface charge density vector.

Sub-vectors on the right-hand side of the system of linear equations (3) can be described using the following expressions:

$$\{\Psi^s\} = \begin{Bmatrix} \bar{\Phi}_1^s \cdot \ell_1 \\ \vdots \\ \bar{\Phi}_{NS}^s \cdot \ell_{NS} \end{Bmatrix} \tag{4}$$

$$\{\Psi^p\} = \begin{Bmatrix} \bar{\Phi}_1^p \cdot \iint_{S_1} N_1^p \cdot dS_1 \\ \vdots \\ \bar{\Phi}_{NP}^p \cdot \iint_{S_{NP}} N_{NP}^p \cdot dS_{NP} \end{Bmatrix} \tag{5}$$

where ℓ_i is the length of the ith cylindrical conductor segment.

3. Computation of the scalar electric potential

By adopting limitations that the cylindrical conductor segment linear charge density is approximated by a constant, and that the surface charge is placed on the surfaces of NP spatial 2D finite elements, the scalar electric potential distribution at the arbitrary field point $T(x, y, z)$ in the air of the observed two-layer medium can be written as:

$$\begin{aligned} \bar{\varphi} = & \sum_{j=1}^{NS} \frac{\bar{\lambda}_j}{4 \cdot \pi \cdot \varepsilon_0} \cdot \left(\int_{\Gamma_j} \frac{d\ell_j}{R_j} + \bar{k}_r \cdot \int_{\Gamma_{j^s}} \frac{d\ell_j}{R_{j^s}} \right) \\ & + \sum_{j=1}^{NP} \sum_{q=1}^{NC_j} \frac{\bar{\sigma}_j^q}{4 \cdot \pi \cdot \varepsilon_0} \cdot \left(\iint_{S_j} \frac{N_j^q \cdot dS_j}{R_j} + \bar{k}_r \cdot \iint_{S_{j^s}} \frac{N_j^q \cdot dS_j}{R_{j^s}} \right) \end{aligned} \tag{6}$$

where $\bar{\lambda}_j$ is the phasor of the jth cylindrical conductor segment linear charge density, $\bar{\sigma}_j^q$ is the phasor of the surface charge density joined to the qth local node of the jth spatial 2D finite element, N_j^q is the shape function joined to the qth local node of the jth spatial 2D finite element, Γ_j is the integration path positioned along the jth cylindrical conductor segment axis, Γ_{j^s} is the integration path positioned along the axis of the jth cylindrical conductor segment image, S_j is the surface of the jth spatial 2D finite element, S_{j^s} is the image of the jth spatial 2D finite element surface, R_j is the distance between the field point and a source point, R_{j^s} is the distance between the field point and a source image point, and $\bar{k}_r$ is the reflection coefficient.

The boundary conditions are potentials of cylindrical conductor segments and spatial 2D finite elements, zero potential of the Earth’s surface and zero potential at infinity.

In order to compute scalar electric potential and consequently electric field intensity, one needs to take into account the effects of