3D Finite Element Analysis of Conductive Coupling Problems in Transmission Line Rights of Way

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***Abstract*—The 3D finite element method is applied to compute conductive couplings in a transmission line right of way. The domain under analysis is composed of several underground structures, such as ground wires of high voltage towers, a coated pipeline section and a steel-reinforced masonry enclosure. A non-homogeneous Dirichlet boundary condition is employed to overcome the modeling difficulties of this particular problem.**

***Index Terms*—Finite element methods, Transmission lines, Pipelines, Grounding, Electromagnetic coupling.**

I. Introduction

The right of way of a power transmission line is a complex electromagnetic environment. During the failure of an insulator or a lightning strike, a non-obvious current pattern flows from the power system to the earth through its metallic towers and their footings [1]. These currents may stress neighboring structures and produce dangerous overvoltages, composing a scenario that belongs to the category of conductive coupling problems in the practice of power engineering.

This current pattern drained to earth has been modeled with the aid of both lumped circuit and field theory methods [2]. However, these procedures must be complemented with additional tools if a local and detailed modeling of the right of way is required. This paper aims to provide such a tool and employs the finite element method (FEM). Previous works by other authors focused upon the inductive coupling to long parallel structures, and hence could take advantage of 2D FEM formulations [3]. The conductive coupling problem here considered requires a 3D formulation. The particular situation, the detailing of the numerical procedure and the results obtained are exposed in the next sections.

II. The Conductive Coupling Problem Under Analysis

The problem is depicted in Fig. 1. It shows the surroundings of an area spanned by two towers of a transmission line close to an underground pipeline section (1.04 m deep), which is made accessible to personnel inside a steel-reinforced masonry structure (4.0 m × 3.35 m × 2.4 m). The aim is to investigate the mitigatory role played by the embedded steel reinforcements, that is, their ability to modify the electric potential distribution next to the working area and to lessen touch and step voltages during a contingency.

As described in section I, in case of a power system fault components of power frequency current are injected at each tower's foundations and flow into the soil through their ground networks. Their values are known in advance from a previous system-wide computation, and are available together with other relevant data in Fig. 1. As will be discussed in the next section, the proposed numerical scheme employs these current values both to excite the FEM simulation and to determine appropriate boundary conditions.

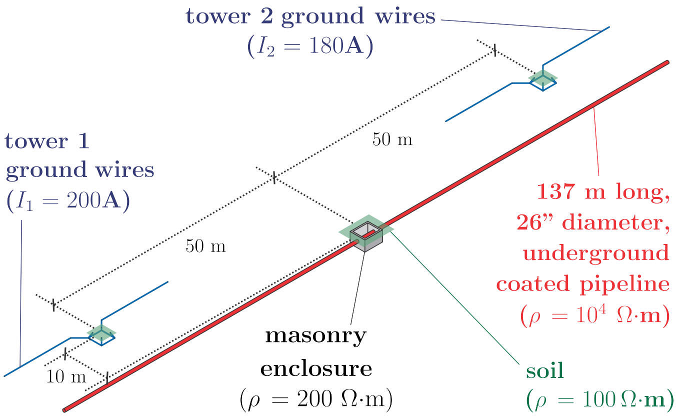

Figure 1: Underground structures sharing the transmission line right of way.

III. Finite Element Formulation for Conductive Coupling Problems in Power Systems

In the conductive coupling between transmission lines and nearby structures, the currents flowing in the earth are governed by Maxwell's equations. In the absence of an impressed current density $\vec{J}_o$, these equations may be transformed to the frequency domain and gathered in the form below:

$$\nabla \times \left(\nu \nabla \times \vec{A}\right) + \dot{\sigma}\left(j\omega\vec{A} + \nabla V\right) = 0 \text{ in } \Omega, \qquad (1)$$

in which $\vec{A}$ is the magnetic vector potential and V is the electric scalar potential. The material properties ν and $\dot{\sigma}$ are the media's reluctivity and complex conductivity, respectively. The domain Ω is to be associated with the soil under a transmission line span, as well as the structures embedded in it (e.g. tower ground wires, pipelines and masonry). It is bounded by a surface Γ, which may be subdivided into two regions. The first one, Γ_S, coincides with the soil surface under the hanging transmission line conductors. The second one, Γ_U, lies beneath the earth surface, and is the one which actually truncates the domain representation underground.

A weak form of the boundary value problem given by (1) is obtainable by the 3D AV edge element formulation [4]. The following subsections will provide further information on the specific implementation of this formulation here employed.

A. *Thin wire model for ground wires and steel reinforcements*

The difference of scale between thin conductors and the total length of the transmission line span represents a well-known challenge for FEM computations. In this work, the scheme proposed in [5] was applied for such a task.

B. *Boundary Conditions*

The 3D AV edge element formulation requires boundary conditions on Γ_U for the electric potential V. These conditions should emulate an unbounded domain, and this necessity is taken into account with the aid of the following expression:

$$V_j = \sum_{k=1}^{n} \frac{\rho\, I_k}{2\pi\, r_{jk}}. \tag{2}$$

Equation (2) computes a non-homogeneous Dirichlet boundary condition for the j-th mesh node lying on Γ_U. The currents I_k are the field sources responsible for exciting the FEM model, and their values equal the previously computed fault currents. They are considered as being punctually injected on surface Γ_S. The soil resistivity is given by ρ and r_{jk} is the distance from the k-th point source on Γ_S to the j-th point on Γ_U. The following assumptions are implied in (2):

- The soil may be represented by a single resistivity ρ.
- The frequency of the currents I_k is low enough.
- The domain Ω is made sufficiently large.

IV. RESULTS AND CONCLUSION

The application of the numerical scheme just described to the conductive coupling problem of section II yields an algebraic system of equations. The solution of this system provides the electric potential distribution in Ω. Figure 2 shows a general view of this distribution and brings further implementation details of the numerical model obtained.

The investigation of the mitigatory effect of steel reinforcement bars is accomplished with the aid of Fig. 3, in which a detail of the enclosure is shown. Evaluation of the electric potential distribution on its floor reveals that a subject stepping on the spot marked with an X and touching a perfectly grounded structure at 0 V would experience a touch voltage of 42.9 V. A previous computation disregarding the existence of steel reinforcements furnished 122.0 V for the same touch voltage.

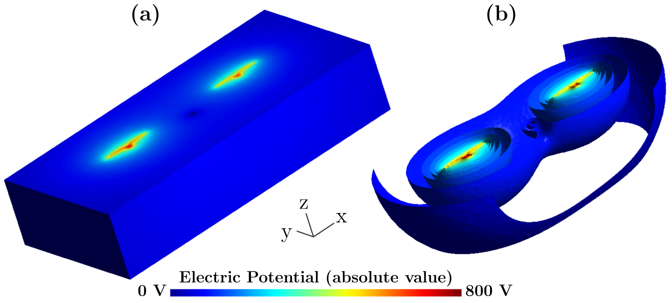

Figure 2: Overview of the solution (a) and its equipotential surfaces (b). Discretized with tetrahedra (4 nodes, 6 edges). Unknowns in system of equations: ≈ 2 200 000.

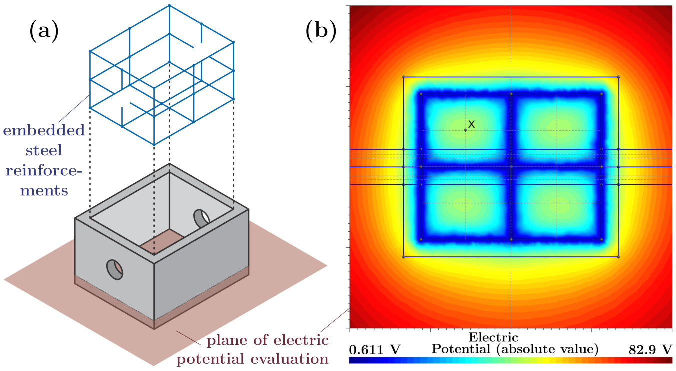

Figure 3: Detail of the masonry enclosure (a) and the plane of electric potential evaluation (b).

The boundary condition procedure exposed in subsection III-B is an extension of the one proposed in [6], and arises from the superposition of effects of n point sources. Though somehow restrictive, its implied assumptions are met by the problem outlined in section II and would also certainly be satisfied in other real conductive coupling problems of interest. The proposed approach takes good advantage of the fault currents determined in advance, making it well-suited for the 3D FEM analysis of rights of way. Also, its use is straightforward and avoids more specialized methods for dealing with the boundary (e.g. PML or transformations of coordinates).

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