Magnetic Field Mitigation Shielding of Underground Power Cables by Using a FEM/BEM Technique

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Abstract — This paper is a contribution to the analysis of magnetic field mitigation shielding of underground power cables. A hybrid FEM/BEM is adopted for the numerical treatment of the open boundary magnetic field problem. Different constitutive materials for the magnetic shielding are studied, and comparison is established between conductive (aluminum) and ferromagnetic (steel) cases. A horizontal flat configuration for the underground cable is considered. It is concluded that the aluminum shielding is more efficient as far as magnetic field mitigation is concerned.

I. Introduction

More and more remarkable efforts have been devoted to research activities aiming to attain suitable and accurate models to simulate the electromagnetic field created by underground power cables. Two facts justify the increment of these efforts: (1) spreading of urban centers requires increasingly convergent electric power flux guided by underground power systems; and (2) danger to human health is a current matter of concern and controversy regarding the exposure to electric and magnetic fields (EMF) at extremely low frequency (ELF), namely at power frequency.

In particular, possible adverse health effects due to power frequency magnetic fields have become one of the most discussed issues.

Since the 1920s [1]-[5] methods have been developed to evaluate accurately magnetic field quantities due to underground power cables. At early times analytical methods were used [3]-[5] but, more recently, numerical methods have grown in importance [1], [7], [9], in order to obtain more realistic models taking into account the presence of inhomogeneity, nonlinearity, and complex configurations.

On the other hand, solutions have been analyzed to mitigate the magnetic field, in particular for high voltage transmission underground cables. These solutions may be classified into two groups: (1) "intrinsic methods" where cable parameters themselves are under attention for mitigation purposes, for certain phase arrangements or compacting strategies [10]; and (2) "extrinsic methods" where external apparatuses are used such as grids of insulated conductors [6] or shields made of ferromagnetic or conductive materials [7]-[9].

This paper deals with extrinsic techniques by using a magnetic field mitigation shielding for underground power cables.

A finite width ferromagnetic or conductive shielding is installed in the soil parallel to the soil/air plane surface covering a three phase power underground system composed by three cables in flat configuration. In this case a numerical method must be used such as the finite element method (FEM). In [7] the finite elements spread out as far as the location of an adequate far away fictitious outer boundary where the magnetic filed is considered negligible. To avoid this disadvantage, and in order to optimize the FEM discretization, a hybrid FEM/boundary element method (BEM) is used in this paper, according to the rationale described in [1]. This paper is a sequel of [1], where the numerical method was validated by using certain special problems with analytical solutions. In this paper the aim is to use the method for the described purposes. However, results are even compared with those obtained by employing other techniques [2], [7], allowing the verification of all different techniques together.

II. Magnetic Field Formulation and Numerical Results

The mitigation shielding technique for the magnetic field due to power transmission underground systems constitutes an open boundary field problem. The hybrid method developed in [1] is adopted. The finite element method (FEM) inside a region surrounded by a regular fictitious surface is combined with a semi-analytical boundary element method (BEM) to describe the field outside this region. In this paper, a two-dimensional (2D) periodic time-harmonic electromagnetic field problem is considered for the underground transmission system in which eddy currents inside phase conductors and the soil are taken into account. A fictitious cylindrical surface located in the soil is considered in a way such that the open space is partitioned into two regions: the inner region containing the power cables (and other apparatuses eventually with irregular shapes – where the magnetic shields are included) and, the outer region composed by the soil and air separated by a plane surface.

A FEM formulation is used for the inner region [1]. The magnetic vector potential is taken as the primary quantity.

For the outside region, a generalization of Pollaczek´s solution [7] is applied, like the one referred in [1], taking into account eddy currents in the soil and the proximity effect between the soil/air plane surface and the cylinder fictitious surface with finite radius. In this way, the outside field description is based on a Fourier series development over the cylinder fictitious surface for the potential and for its normal derivative values. These quantities, discretized and organized into finite dimension vectors, are related by using formulae derived analytically and expressed as a square coefficient matrix. A Discrete Fourier Transform (DFT) is then used to transform the relationship to the space domain where it assumes the form of another coefficient matrix relating the actual potential values with their normal derivatives over a set of discrete nodes on the fictitious separating surface. These nodes are coincident with the discrete nodes of the FEM mesh taken for the inner region.

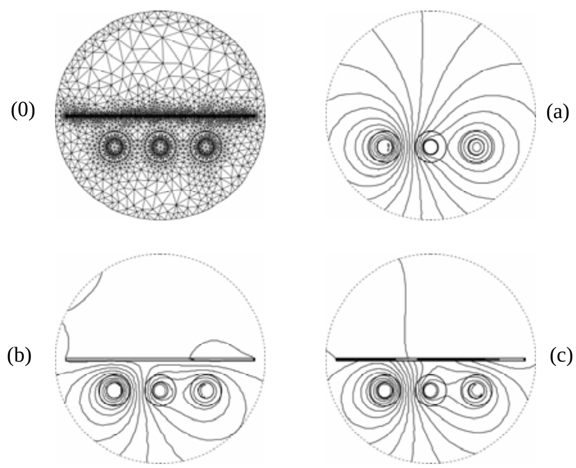

Fig. 1. FEM mesh (0) and magnetic field lines in the inner region at the instant where the current of phase 1, flowing in the conductor on the left, has a maximum value: (a) without shielding; (b) with conductive (aluminum) shielding; (c) with ferromagnetic (steel) shielding.

The magnetic field for the internal region may be established, as described in [1], by using an appropriate variational formulation where the magnetic vector potential appears as the primary quantity. The FEM formulation involves both the unknown potential values of the FEM nodal points as well as the potential normal derivative values on the nodes of the fictitious surface. The relationship allows boundary conditions on the above referred surface to be matched with the field formulation for the outer region.

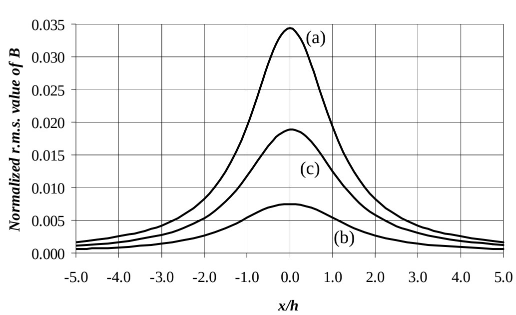

Fig. 2. Normalized *r.m.s.* value of the induction magnetic vector along the soil/air surface for the cases (a), (b), (c) described in Fig.1.

Numerical results are obtained for a typical high voltage three phase cable: each individual cable has an outer radius r_e=7.4 cm, a copper phase conductor with radius r_c=3.6 cm, a cable inter-spacing s=21.8 cm and where the fictitious boundary is buried at a depth h=1.352 m. The distance between the centers of the central cable and the fictitious boundary is 14.8 cm. The shielding is centered at the center of the fictitious boundary with a width w=90 cm and a thickness t=10 mm. The working frequency is equal to 50 Hz and the soil conductivity is 10^{-2} Sm^{-1}. The influence of the lead cable sheaths may be neglected because sheaths are taken disconnected, and, in addition, the sheath thickness is much smaller than the corresponding field penetration depth. Fig. 1 shows the FEM mesh adopted for the cases with magnetic shielding, as well as the magnetic field lines at an instant when the current of phase 1 has a maximum value. Fig. 2 represents the normalized *r.m.s.* value of the magnetic induction vector along the soil/air surface denoted by the co-ordinate x, where x=0 corresponds to the horizontal location of the central cable. The magnetic induction is evaluated as indicated in section IV of [1] and the normalization factor is taken as $\mu_0 I_{r.m.s.}/h$. Results in the absence of shielding (case (a)) agree with those obtained in [2] with a deviation less than 3%. The reduction factor (*RF*) [7] is defined as the ratio between the *r.m.s.* value of the magnetic induction field on the soil/air plane at x=0 for the cases without and with magnetic shielding. The obtained *RF* values are equal to 4.6 and 1.82 for the aluminum and steel shielding cases, respectively. On the other hand, for the underground cables and the magnetic shields presented in [7], deviations in *RF* less than 3% were found.

ACKNOWLEDGEMENT

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III. REFERENCES

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