An Investigation of Magnetic Field Influence in Underground High Voltage Cable Shields

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Abstract-Magnetic fields and the shielding efficiency of the shields of underground high voltage cables are studied in this paper regarding several shielding configurations and materials. Shielding efficiency and magnetic fields are computed for shields with the same mesh but from different shielding materials, such as aluminum, ferrite, metal, and steel. In order to get the best shield configuration depending on the source characteristics and the material, a conducting ferromagnetic region with various thickness values is considered as shielding. A finite element model is introduced to investigate the influence of the parameters of magnetic fields and the shielding efficiency of underground high voltage cables. Furthermore, the reduction of the magnetic fields with or without shieldings is also presented. The developed method is performed with the magnetic vector potential formulations and validated on a practical problem.

Keywords-shielding efficiency; magnetic fields; eddy currents; underground power cables; finite element technique

I. INTRODUCTION

Magnetic fields cause a considerable disturbance of the operation and accuracy of sensitive electrical and electronic devices [1], while they pose an important issue to public health [2-5]. New regulations involving a drastic reduction of the allowable limits of exposure have been developed. Unfortunately, the conclusion for that problem is not clear and, even if it is, it is still disputed. It cannot be concluded surely that there is no relation between magnetic fields and certain diseases. In addition, a lot of shield configurations can be used as magnetic shielding for underground high voltage cables such as open and closed shield structures. As proposed in [6], the use of thick and large flat sheets above underground high voltage cables gives a good shielding performance. This is also right for a minimal distance between shields and high voltage cables. In addition, good shielding efficiency is demonstrated for closed shield structures [7-9]. In [10], a unimoment method has been proposed to analyze the magnetic shielding of a source within a steel pipe made of ferromagnetic material. In [11], an analytic method has been developed for computing the losses in steel casting with an arbitrary cable arrangement. In [12], the power losses have been computed following the statistical theory. For the above reasons, remarkable efforts have been devoted to research activities aiming at studying suitable techniques to achieve the desired reduction of the magnetic fields generated by electrical systems. In many cases this can be done by simple and effective solutions that do not mean costly additional investments.

Magnetic Fields (MFs) can be generated by high voltage transmission underground cables. Several methods have been applied to compute the MFs. They are generally categorized as internal and external shielding methods [12-15]. Although the obtained results from these methods are successful to a great degree in some cases, these techniques have also some drawbacks.

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In this paper, the influence of the parameters of the MFs on the shieldings covering underground high voltage cables with different cases of several configurations have been analyzed and simulated via finite element method. This will be presented with the magnetic vector potential formulations to compute and investigate the influence of the MFs and the reduction factor in the proximities due to the field sources. The developed method is validated on the practical problem.

II. MAGNETIC SHIELDING PROBLEMS

A. Shielding Problems of Underground High Voltage Cables

Shielding is the most efficient solution to reduce the MFs generated by underground high voltage cables. Two different shields can be considered: open shields and close shields. The open shield consists of a cover (flat) plate located above the high voltage cables (Figure 1), and the close shield consists of a cable tray surrounding the cables (Figure 1). The second case is more expensive than the first case, which is usually employed to reconfigure existing systems. The conductive materials for both cases can be made of aluminum, copper, or ferromagnetic materials. This selection is very important, because each material provides different shielding. There are two scenarios: If the shielding is a high conductive material, the reduction of the field is based on eddy current cancellation. This means that the eddy currents are induced in the conductive plate due to the MFs that partially cancel those of the source as pointed out in Figure 2. If the shielding is a material with high permeability, the mechanism is known as flux shunting. This means that the magnetic flux density generated by the source is diverted into the magnetic material and away from the region to be shielded, as shown in Figure 3.

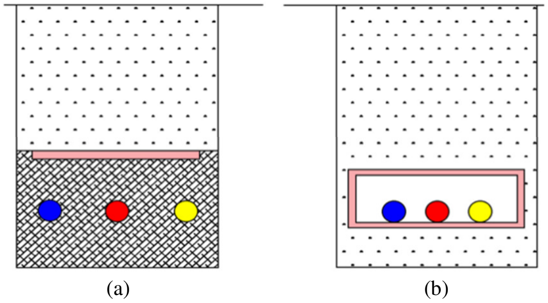
(a) (b)

Fig. 1. (a) Open shield, (b) close shield.

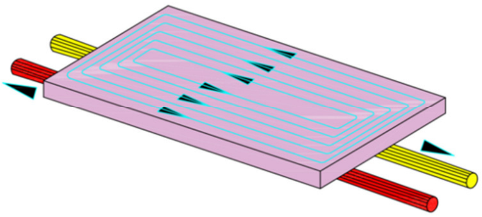

Fig. 2. Eddy current distributions in a cover plate.

These two scenarios are characterized by different Boundary Conditions (BCs) which have to be analyzed in each configuration. From the above analysis, it is clear that it is not important to decide which shielding technique is the best to mitigate the field caused by an underground high voltage cable, because the shielding effectiveness depends on the configuration of the cables, with issues such as the distance between the cables and the shield, the thickness and width of the plate, etc. Depending on the different properties of materials, the results obtained with magnetic materials differ from those obtained using conductive materials. The close shield usually gives a high field reduction near the source, whereas the open shield provides better results far from it. This is also strongly influenced by the arrangements (locations) of the cables. High conductive open shields are suitable for flat lines. However, for the vertical lines, the open shields made of ferromagnetic materials perform better [1]. Moreover, it should be noted that magnetic materials are usually more expensive than conductive materials. For the above reasons, a full study/analysis of the parameters involved directly with the effectiveness of shields is presented in this paper to give a selection of suitable configurations for electrical systems. The considered shield parameters are:

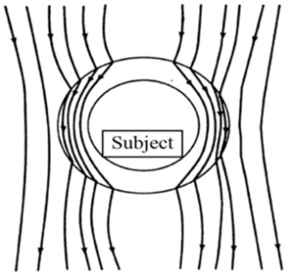

Fig. 3. Flux shunting shielding.

- Thickness and profile of the plate.
- Value of magnetic permeability and electric conductivity.
- Different types of materials used.
- The distance from the source and the relationship with the dimensional characteristics of the source.

B. Canonical Magnetodynamic Problems

A canonical magnetodynamic problem is defined in a domain Ω, with boundary $\partial\Omega = \Gamma = \Gamma_h \cup \Gamma_e$. The Maxwell's equations considered in the frequency domain and behavior laws are written in Euclidean space $\mathbb{R}^3$ [16-18]:

$$\operatorname{curl} \mathbf{H} = \mathbf{J}_s, \operatorname{curl} \mathbf{E} = -j\omega\, \mathbf{B},\ \operatorname{div} \mathbf{B} = 0 \quad \text{(1a-b-c)}$$

$$\mathbf{B} = \mu\mathbf{H},\ \mathbf{J} = \sigma\mathbf{E} \quad \text{(2a-b)}$$

where $\mathbf{H}$ is the magnetic field (A/m), $\mathbf{B}$ is the magnetic flux density (T), $\mathbf{E}$ is the electric field (V/m), $\mathbf{J}_s$ is the current density (A/m^2), μ and σ are the relative permeability and the electric conductivity (S/m).

The BCs defined on Γ are expressed as:

$$\boldsymbol{n} \times \mathbf{H}|_{\Gamma_h} = \boldsymbol{j}_f,\ \ \boldsymbol{n} \cdot \mathbf{B}|_{\Gamma_e} = \boldsymbol{b}_f \quad \text{(3a-b)}$$

where $\boldsymbol{n}$ is the unit normal exterior to Ω, with $\Omega = \Omega_c \cup \Omega_C^c$. The domains Ω_c and Ω_C^c are respectively the conducting and non-conducting regions. Equations (1a) and (1b) are solved with BCs taking the tangential component of **H** in (3a) and the normal component of **B** in (3) into account.

The fields **H, B, E,** and **J** are defined to satisfy Tonti's diagram [9]. This means that $\mathbf{H} \in \boldsymbol{H}_h(\text{curl};\Omega)$, $\mathbf{E} \in \boldsymbol{H}_e(\text{curl};\Omega)$, $\mathbf{J} \in \mathbf{H}(\text{div};\Omega)$, and $\mathbf{B} \in \boldsymbol{H}_e(\text{div};\Omega)$, where $\boldsymbol{H}_h(\text{curl};\Omega)$ and $\boldsymbol{H}_e(\text{div};\Omega)$ are function spaces containing the BCs and the fields defined on Γ_h and Γ_e of the studied domain Ω. The fields $\boldsymbol{j}_f$ and $\boldsymbol{b}_f$ in (3) are generally equal to zero for classical homogeneous BCs. The field $\boldsymbol{b}$ in (1c) is derived from a vector potential $\boldsymbol{a}$ such that:

$$\boldsymbol{b} = \text{curl}\,\boldsymbol{a} \quad (4)$$

By combining (4) with (1b), we have $\text{curl}\,(\boldsymbol{e} + \partial_t\boldsymbol{a}) = 0$, which leads to the definition of an electric scalar potential v such that:

$$\boldsymbol{e} = -\partial_t\boldsymbol{a} - \text{grad}\,v \quad (5)$$

C. Magnetic Vector Potential Weak Formulations

Based on the weak form of Ampere's law (1a), the weak formulation of magnetic problems is written as [17-21]:

$$(\mu^{-1}\boldsymbol{b}, \text{curl}\,\boldsymbol{a}')_{\Omega} - (\sigma\boldsymbol{e}, \boldsymbol{a}')_{\Omega_c} + \langle \boldsymbol{n} \times \boldsymbol{h}, \boldsymbol{a}' \rangle_{\Gamma} =$$

$$(\boldsymbol{j}_s, \boldsymbol{a}')_{\Omega_s}, \ \forall\, \boldsymbol{a}' \in \boldsymbol{H}_e^0(\text{curl},\ \Omega) \quad (6)$$

By substituting the magnetic flux density $\boldsymbol{b}$ from (4) and the electrical field $\boldsymbol{e}$ from (5) into (6), we get:

$$(\mu^{-1}\text{curl}\,\boldsymbol{a}, \text{curl}\,\boldsymbol{a}')_{\Omega} + (\sigma\partial_t\boldsymbol{a}, \boldsymbol{a}')_{\Omega_c} + (\sigma\,\text{grad}\,v, \boldsymbol{a}')_{\Omega}$$

$$+\langle \boldsymbol{n} \times \boldsymbol{h}, \boldsymbol{a}' \rangle_{\Gamma_h} = (\boldsymbol{j}_s,\ \boldsymbol{a}')_{\Omega_s}, \ \forall\, \boldsymbol{a}' \in \boldsymbol{H}_e^0(\text{curl},\ \Omega) \quad (7)$$

where $\boldsymbol{H}_e^0(\text{curl},\ \Omega)$ is a function space defined on Ω containing the basis functions for $\boldsymbol{a}$ as well as for the test function $\boldsymbol{a}'$. Notations $(\cdot,\cdot)$ and $<\cdot,\cdot>$ are respectively a volume integral and a surface integral of the product of their vector field arguments.

The surface integral term $\langle \boldsymbol{n} \times \boldsymbol{h}, \boldsymbol{a}' \rangle_{\Gamma_h}$ on Γ_h in (8) accounts for natural BCs that can be locally specified. This is the case for a homogeneous Neumann BC, e.g. imposing a symmetry condition of "zero crossing current", i.e.:

$$\boldsymbol{n} \times \boldsymbol{h}|_{\Gamma_h} = 0 \Rightarrow \boldsymbol{n} \cdot \boldsymbol{b}|_{\Gamma_h} = 0 \ \Leftrightarrow\ \boldsymbol{n} \cdot \boldsymbol{j}|_{\Gamma_h} = 0 \quad (9)$$

III. PRACTICAL TEST

The test problem considered for the 2D model is a shielding problem with different configurations.

TABLE I. PROPERTIES OF SHIELDING MATERIALS [5, 8]

Material	**Conductivity (σ) S/m**	**Relative permeability (μ_r)**
Aluminum	3.8×10^7	1
Steel	10^7	500
Metal	1.64×106	15,120
Ferrite	2	10,000

Three different cases of a flat arrangement of the underground high voltage cables were considered (Figure 4): (a) a cover plate shield (horizontal plate shield) located above the three conductors, (b) a reverse- U shield, and (c) close shield surrounding the three conductors. In all cases, the three conductors are supplied by balanced currents of 100A at a frequency of 50Hz and Voltage of 132kV. Cable depth is fixed at 80cm, with a separation between cables of 25cm and conductor diameters of 20mm.

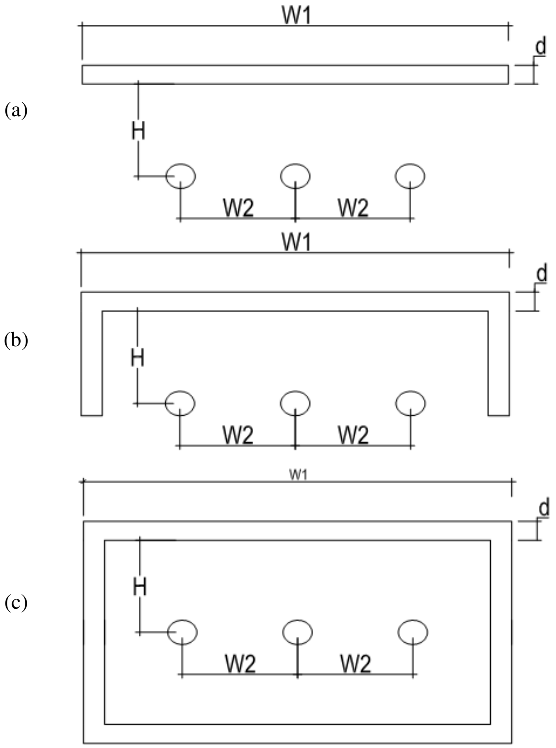

Fig. 4. Geometry of high voltage cables with different configurations: (a) no shield, (b) reverse U-shield, and (c) close shield.

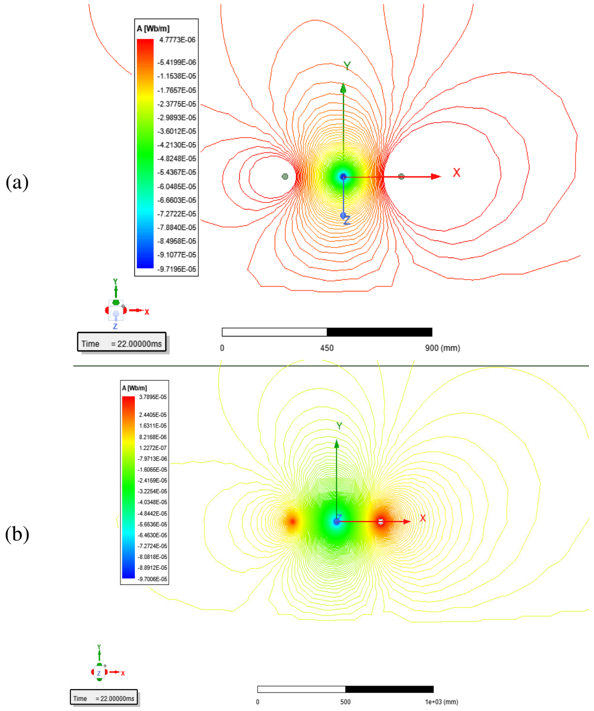

Fig. 5. Field lines in cover shield of (a) aluminum and (b) ferrite.

The influence of geometrical parameters of the high voltage cables and the shield in the field generated at 1m height above the ground has been studied. The influence in the shielding factor (also called the reduction factor) can be defined as:

$$RF = \frac{B_0}{B} \quad (10)$$

where B_0 is the root mean square (RMS) value of the field density without the shield, and B is the RMS value of the field with the shield in place. By another way, SF can be considered as a position function of the shield. The biggest the SF is, the more significant the magnetic field reduction. The properties of shielding materials are given in Table I [5, 8].

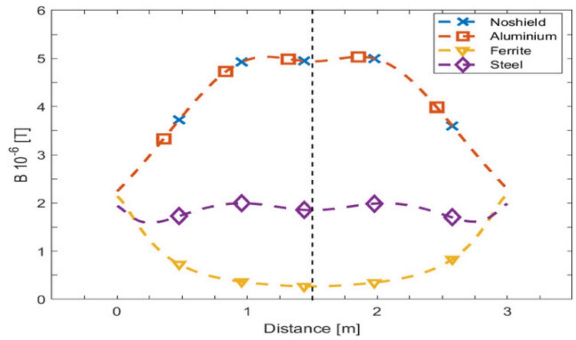

Fig. 6. Magnetic flux density distribution for different material shieldings (horizontal shield).

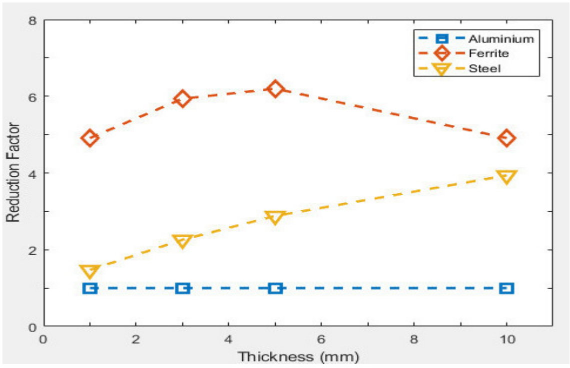

Fig. 7. Reduction factor process with different thicknesses.

Two different cases are now considered for testing: Without and with cover shield. The distribution of the field lines for the different material shields is presented in Figure 5, where field lines can divert in the proximity of the cover shielding due to the different materials. The value of magnetic flux density along the shield at 1m above the ground is pointed in Figure 6, for the cases without shield and with shields from different materials (aluminum, ferrite and steel). From the obtained results, it can be seen that the magnetic flux density distribution is very high for the cases without shield and with aluminum shield in comparison with the cases of the ferrite and steel shields, because the massive fields mostly focus on these materials with a little flux leakage to the surrounding air. This means that the magnetic inductions are almost refracted into these shields. The influence of magnetic flux density distribution in the final cost of the cover shield depends on its thickness. Thus, there are several cases of thickness values from 1mm to 10mm for the considered materials which have to be examined. The relation of the RF with the shield thickness given in (10) is indicated in Figure 7. It should be noted that the value increases when the thicknesses varies from 1 to 5mm for ferrite materials. From 6 to 10mm, the value of RF reduces noticeably. The influence of steel thickness increases noticeably from 1 to 10mm, while the thickness influence of aluminum material can be ignored. For the case of reverse-U shield, the field lines of aluminum and ferrite are illustrated in Figure 8. The process of RF with different materials and thicknesses is presented in Figure 9. The RF for steel, metal, and ferrite increases noticeably with thickness from 1 to 10mm as shown in Figure 10. On the other hand, the influence of the aluminum shielding is weak and not worth considering. Similarly with Figure 6, the reluctances of ferrite and steel are smaller than the air's (no shield case). Due to this, massive fields mostly focus on these materials with a little leakage flux.

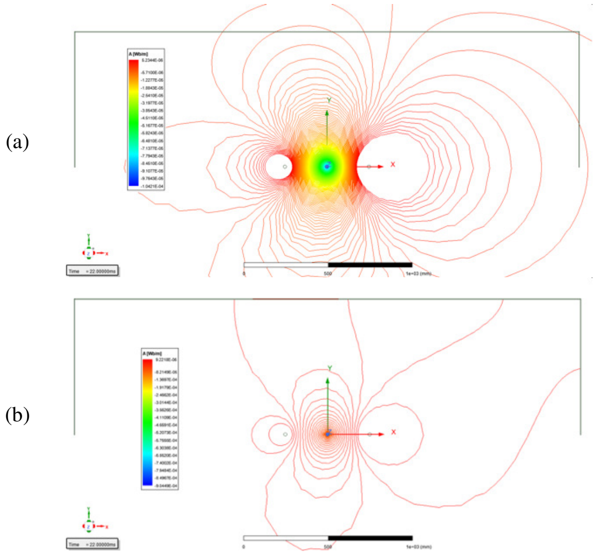

Fig. 8. Field lines in reverse-U shield of (a) aluminum, (b) ferrite.

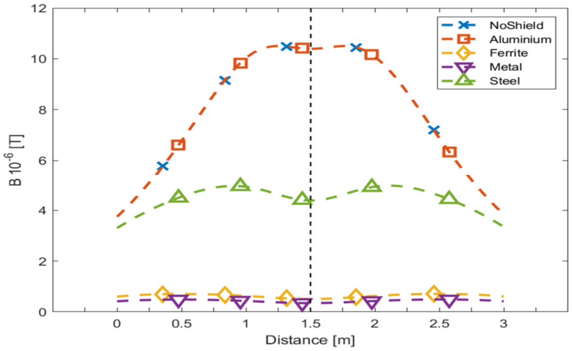

Fig. 9. Magnetic flux density distributions with different material shieldings (reverse- U shield).

Regarding the closed shield, the field lines on magnetic vector potentials are presented in Figure 11. The magnetic flux density distribution with different material shieldings is shown in Figure 12. It can be seen that the results of metal and ferrite materials are improved, getting similar to those obtained from the case of reverse- U shield (Figure 9).

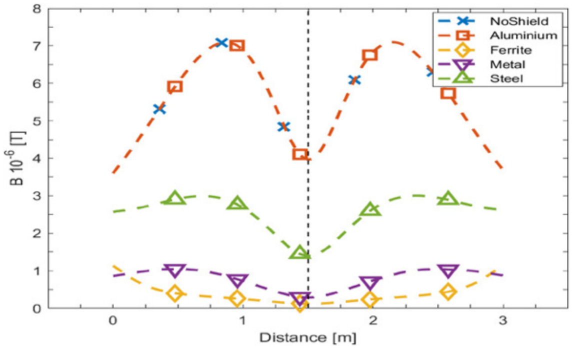

Fig. 10. Process of RF with different materials in reverse-U shield.

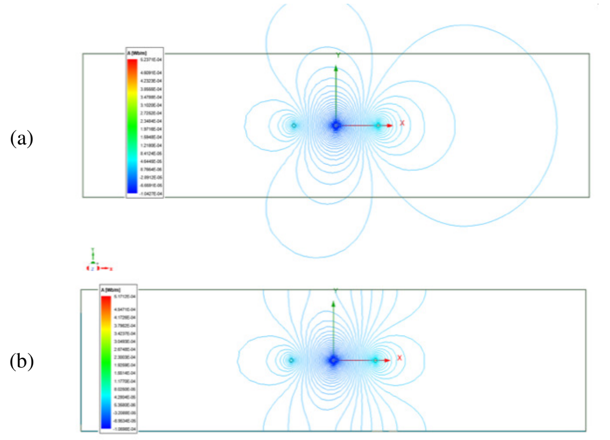

Fig. 11. Field lines in closed shield of (a) alumimum, (b) ferrite.

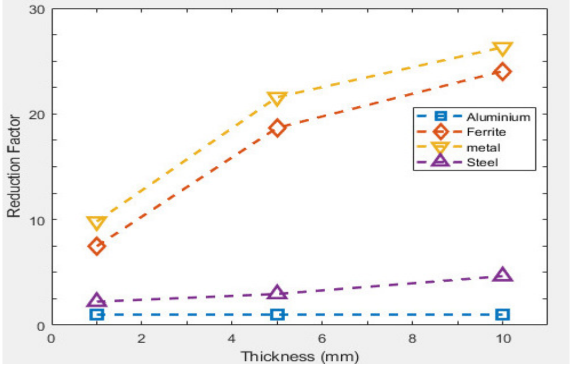

Fig. 12. RF with different material shieldings (closed shield).

IV. CONCLUSION

In this paper, the influence of magnetic flux density distribution on shielding efficiency for underground high voltage cables has been investigated with the magnetic vector potential formulations for several shielding configurations. Regarding the shielding materials, the obtained results illustrated the influence of magnetic fields at 1m for the cases without shield and with shields from different materials, and the evolution of RF with thickness. High RF can be also obtained by increasing shield thickness when open shield made of high conductive materials is used. In the case of ferromagnetic materials, increasing shield thickness has a low effect. As a result, we can say that shield size has a relatively small effect on shielding: a larger shield decreases slightly the shielding efficiency of ferromagnetic shields, and increases it for shields made from aluminum. In fact, with increasing shield thickness, the shielding effectiveness improves without causing higher losses. In particular, it should be noted that if the best shielding effectiveness for a given thickness is required, a high permeability material is preferred. If a low cost per meter of shield is required, a ferromagnetic grade with lower permeability can be used. If low magnetic losses in the shield are important, aluminum is preferred.

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