# Magnetic field shielding of underground power cables in urban areas: a real-life example

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## Abstract

In this paper the authors propose a parametric analysis of a typical 150 kV underground power cable line laid in urban areas. A coupled electro-magnetic and thermal formulation based on a finite element model (FEM) has been applied to estimate the magnetic pollution due to trefoil configuration or flat configurations at the thermal operating limit of the cables (cable ampacity). We also investigate the performances of open or closed shields, made of conductive and/or magnetic materials, in order to reduce the magnetic pollution due to existing or new installations, imposing as limitation the maximum admissible operative temperature of the cables. The influence of the effective operating conditions on the magnetic pollution generated by the power line has also been investigated. The proposed formulation takes into account the real geometrical dimensions and the effective physical characteristics of the involved materials.
*Keywords: finite element model, coupled electro-magnetic-thermal problem, low-frequency magnetic field, magnetic pollution, shielding.*

## 1 Introduction

During the last decade, the interest in power-frequency magnetic field calculation and shielding is growing due to the increasing concern of possible biological effects of electromagnetic fields on human health. These effects appear to cause or promote certain forms of leukaemia and brain tumours, as suggested by recent epidemiological studies focused on power-frequency magnetic fields. For this reason, in several countries, public concern has probably incited the Regulatory Standards to fix, for the maximum magnetic flux density value, more restrictive limits with respect to the human exposure.

Furthermore, the mitigation of the magnetic field pollution generated by electrical power systems (e.g., underground power lines) has become of great interest, despite the fact that safe and dangerous levels have not yet been established scientifically.

In Italy, the discussion concerning the reduction of the human exposure limits has been closed: in an approved Decree (DCPM 8 July 2003 – G.U. N° 199 del 28 august 2003), the exposure has been fixed at 10 μT for existing electrical power systems, and at 3 μT for new ones.

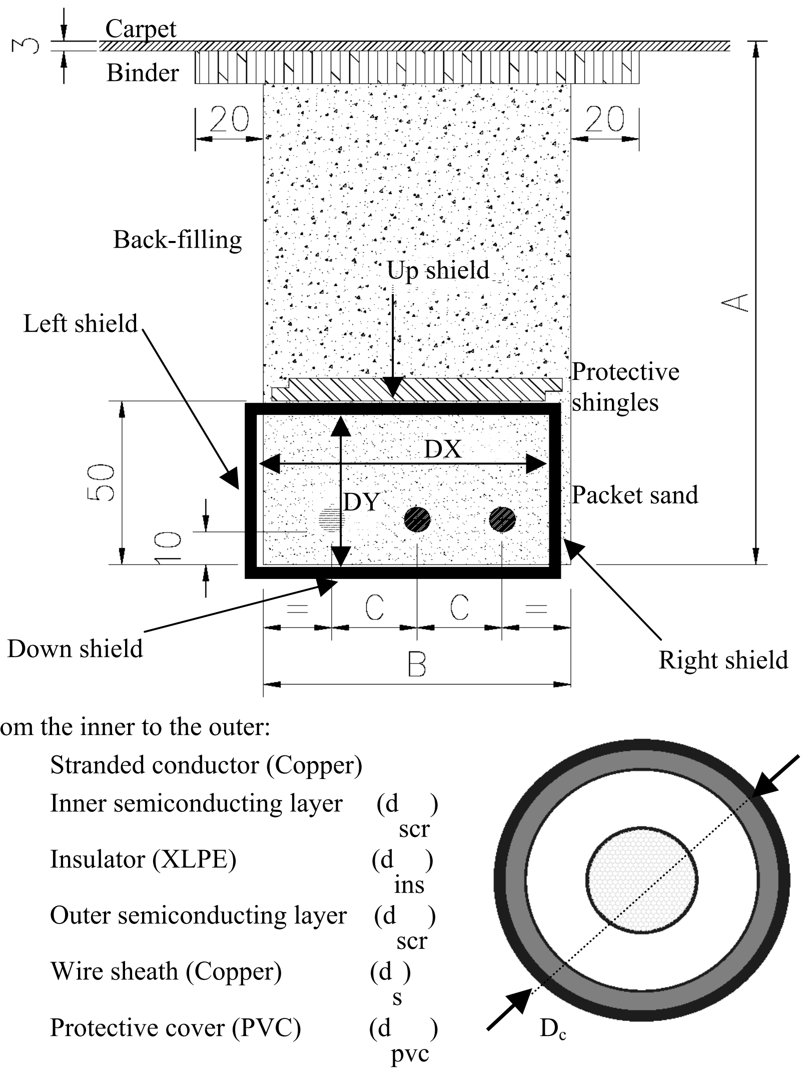
In previous papers [1][2], the authors have presented and discussed the preliminary results of a complete characterization of typical underground power cable lines. In particular, the mitigation of the magnetic pollution, due to a typical underground power line laid in flat configuration, has been analysed in detail by a parametric analysis [1]. This study had the aim to evaluate possible reclamation of existing installations, or accommodation of new installations, by simple passive shielding technologies such as finite width metal shields (made by ferrous or non-ferrous materials). The shielding effectiveness at the ground level (i.e., at 1 m over the asphalt) has been computed varying the shape of the metallic shields (e.g., rectangular, upset U, plane, and so on), their dimensions (thickness and/or width), their positions (between each others or with respect to cables), as well as, their electrical and magnetic properties (resistivity and/or permeability). The results of all simulations shown that simple flat shields can be used in order to reduce the magnetic field levels below the exposure limits fixed by law.

In this paper, the authors propose an improvement of their model by means of which they have analyzed an alternative line geometrical configuration (i.e., the trefoil configuration), and they have also taken into account the thermal aspects related to the effective operating conditions of the power line, according to the model proposed in [2].

The commercial software ANSYS, based on the Finite-Element Method (FEM) [3], has been used to model the electromagnetic and thermal steady-state diffusion problem. Referring to a typical configuration of a three phases 150 kV underground power line (fig. 1), placed in an urban area, parametric calculations and a real-life example are given. The proposed formulation takes into account the real geometrical dimensions and the effective physical characteristics of the involved materials (table 1). The magnetic field distribution, as well as the temperature distribution have been calculated. The cable ampacity has been also estimated starting from the temperature distribution, using as limitation the maximum admissible operative temperature of the cables (i.e., $T_M = 85$ °C).

The assumptions that were used for all calculations are the following:

- the cable is of infinite length (so that the coupled diffusion problem becomes a two-dimensional one);
- charges and displacement currents are neglected;
- the conductors and their sheath have constant relative magnetic permeabilities $\mu_{rc}$ and $\mu_{rs}$ respectively;
- the electrical resistivity, $\rho_c$ and $\rho_s$ of the conductors and their sheath are functions of temperature;



From the inner to the outer:

- Stranded conductor (Copper)
- Inner semiconducting layer $(d_{scr})$
- Insulator (XLPE) $(d_{ins})$
- Outer semiconducting layer $(d_{scr})$
- Wire sheath (Copper) $(d_s)$
- Protective cover (PVC) $(d_{pvc})$

Figure 1: Cross section sketch of a 150 kV underground power cable line laid in urban areas: typical geometrical configurations, planar shield arrangements and high-voltage single-core cable.

| **Configuration** | **A** | **B** | **C** |
|---|---|---|---|
| T1 | 160 cm | 90 cm | 25 cm |
| T2 | 200 cm | 90 cm | 25 cm |
| T3 | 250 cm | 100 cm | 30 cm |
| T4 | 300 cm | 100 cm | 30 cm |

- the thermal conductivities are independent from the temperature (thermal conductivities: $K_c$, conductor – $K_s$, sheath – $K_{ins}$, insulator – $K_{scr}$, semiconducting – $K_e$, soil – $K_{bf}$, back-filling – $K_{ps}$, packet sand – $K_{asph}$, asphalt, i.e. carpet and binder – $K_{psh}$, protective shingles);
- the open or closed shields have the electrical resistivity ($\rho_{Cu}$ or $\rho_{Fe}$ for copper or iron respectively) function of temperature, the magnetic permeability $\mu_{Cu}$ constant while the magnetic permeability $\mu_{Fe}$ constant or varying according to an assigned BH curve (fig. 2), and the thermal conductivity ($K_{Cu}$ or $K_{Fe}$) independent from the temperature;
- the phase currents are sinusoidal and balanced, therefore complex functions for the time variation of the three conductor currents may be used.

## 2 150 kV underground power cable line configuration

A typical configuration of underground power cable lines at 150 kV consists of a trench having standardized dimensions, and in which are placed three high-voltage single-core cables usually laid in flat configuration (fig. 1).

In urban areas, electric cables are directly placed over the soil at the bottom of the trench. They are covered with protective shingles to mark their presence in case of successive digs. Then, the trench is filled by vegetal soil and, finally, it is sealed with a layer of binder.

It has been also considered one or more (up to four) planar shields placed as shown in figure 1.

In this way, it has been possible to analyse the performance of various shield configurations, as well as, the mitigation of the magnetic field pollution varying the shield materials.

Table 1: Geometrical dimensions and effective physical characteristics of the materials.

| **Numerical data** | | $S_c$=1000 mm$^2$ | $D_c$=100 mm |
|---|---|---|---|
| $d_{scr}$=1 mm | $d_{iso}$=22 mm | $d_s$=5 mm | $d_{pvc}$=3 mm |
| $\rho_{co}$=1.8 10$^{-8}$ Ωm | $\rho_{so}$=1.8 10$^{-8}$ Ωm | $\alpha_{c0}$=3.93 10$^{-3}$ 1/K | $\alpha_{s0}$=3.93 10$^{-3}$ 1/K |
| $\mu_{rc}$=1 | $\mu_{rs}$=1 | $K_c$=393 W/mK | $K_s$=393 W/mK |
| $K_{ins}$=0.17 W/mK | $K_{scr}$=0.17 W/mK | $K_{pvc}$=0.17 W/mK | $K_{ps}$=0.8 W/mK |
| $K_{bf}$=1 W/mK | $K_e$=1 W/mK | $K_{psh}$=0.9 W/mK | $K_{asph}$=0.5 W/mK |
| $\rho_{Cu}$=1.8 10$^{-8}$ Ωm | $\rho_{Fe}$=1.33 10$^{-7}$ Ωm | $\alpha_{Cu0}$=3.93 10$^{-3}$ 1/K | $\alpha_{Fe0}$=6.0 10$^{-3}$ 1/K |
| $\mu_{rCu}$=1 | $\mu_{rFe}$=1 | $K_{Cu}$=393 W/mK | $K_{Fe}$=60 W/mK |

It should be pointed out that all simulations are carried out on underground power lines having flat configuration or trefoil configuration. For practical reasons, the trefoil configuration is an unusual laid condition for high-voltage single-core cables; however, it is also a very efficient solution in order to mitigate the magnetic pollution generated by the power line (fig. 3). For this reason, it has been taken into account in this study.

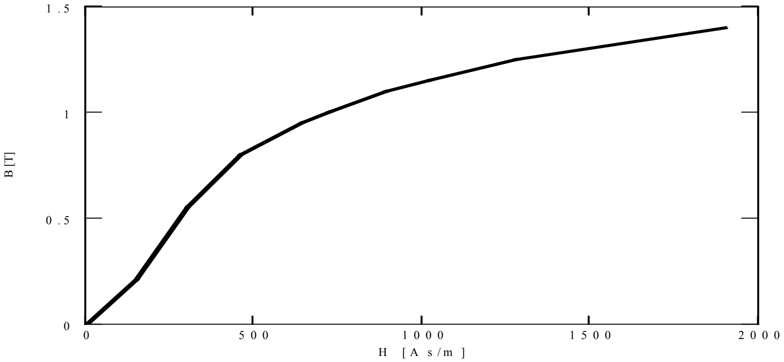


Figure 2: Typical B-H magnetization curve of a commercial iron used for Fe-shields.

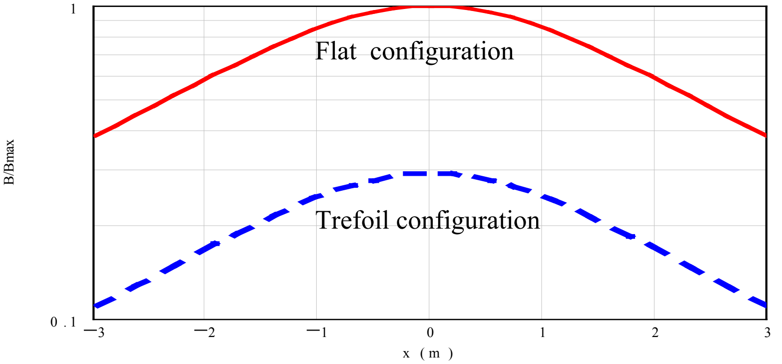


Figure 3: Lateral profile of the magnetic flux density (in p.u.) generated by: a flat configuration (continuous line) or a trefoil configuration (broken line).

# 3 2D finite element model

## 3.1 Electromagnetic problem

The field equations used for the solution of the electromagnetic problem, derive from the Maxwell's one. In a 2D configuration, neglecting electromagnetic propagation phenomena, these relationships lead to the following differential equation:

$$\nabla\times(\upsilon\nabla\times A)=J$$

Additionally, to ensure uniqueness of the vector potential, the "Coulomb gauge" is assumed $\nabla\cdot A=0$.

The previous equation can be written as:

$$-\nabla\cdot(\upsilon\nabla A)+\sigma(T)\nabla V+\sigma(T)\frac{\partial A}{\partial t}=0$$

where: $$J_s+J_e=J \qquad -\sigma(T)\nabla V=J_s \qquad -\sigma(T)\frac{\partial A}{\partial t}=J_e$$

in the conducting region, and

$$-\nabla\cdot(\upsilon\nabla A)=0$$

in the no conducting region.

The differential equation, under opportune boundary conditions, solves the electromagnetic problem and can be studied in time and complex domain, using a FEA approach and imposing global load phase currents. Both skin and proximity effects in massive conductors have been also considered, as well as, the non-linear behavior of Fe-shields (fig. 2).

The magnetic vector's potential $A$, as well as, the source current density, $J_s$, and the eddy currents, $J_e$, are unknowns, while the total current density is specified in integral form:

$$\iint_{S_i} J\,dS=I_{rms_i}\quad i=1,2,3$$

where $I_{rms}$ is the current that flows through the conductor's section $S_c$, and it is the only measurable quantity in the cable.

The power cables operate with a time-harmonic source at the typical power frequency of 50 Hz.

### 3.2 Thermal problem

Thermal steady-state diffusion problem has been solved by the differential equation, which governs the heat conduction

$$-k\,\nabla^2 T= q$$

where $q$ is the rate of heat generated per unit of volume and per unit of time, and $k$ is the thermal conductivity.

The resistivity $\rho(T)$ of the material at $T$ K, according to the assumptions (see § 1), is approximated by

$$\rho(T) = \rho_0(1 + \alpha\,\Delta T)$$

where $\rho_0$ is the resistivity at 293 K, and $\alpha$ is the temperature coefficient of the material. The corresponding boundary conditions are shown in fig. 4.

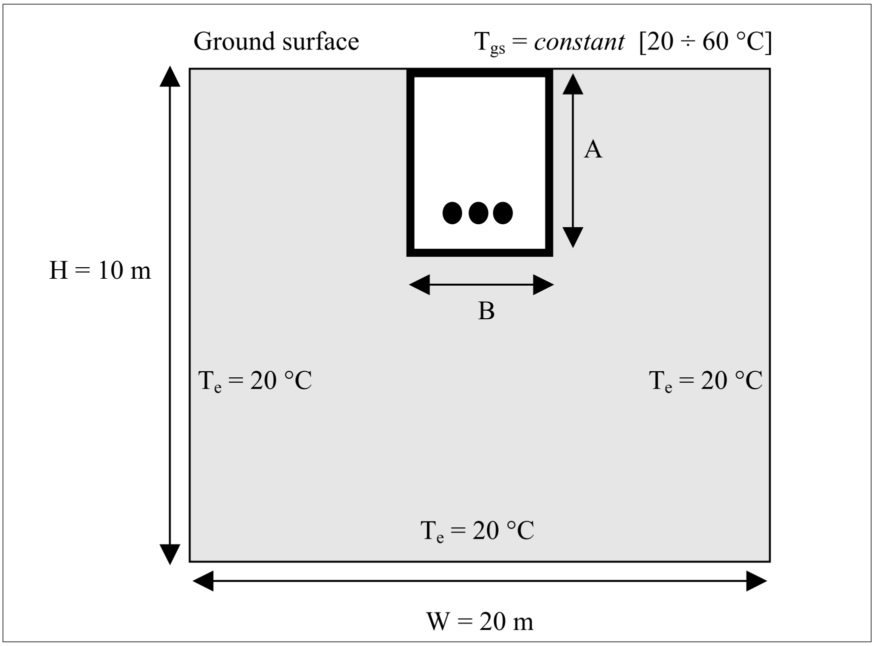


Figure 4: Working hypothesis for the boundary conditions of the thermal problem ($T_{gs}$ is the ground surface temperature, while $T_e$ is the earth temperature).

### 3.3 Coupled electromagnetic and thermal steady-state diffusion problem

The problem is solved using a solution sequence, alternating the electromagnetic harmonic analysis with the steady-state heat transfer analysis, as shown in the block diagram depicted in the next page.

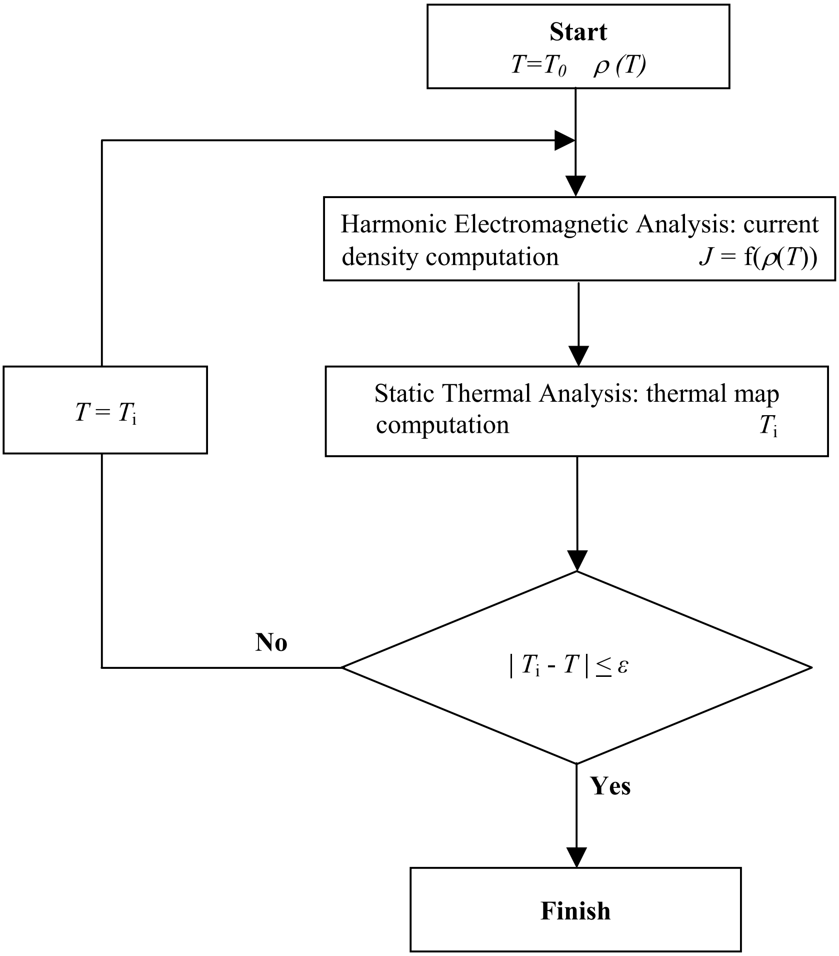
The temperature dependency of electrical resistivity has been considered for the electromagnetic problem. The problem has been solved sequentially, first doing an AC harmonic electromagnetic analysis and then a steady-state thermal analysis. In addition, the electromagnetic analysis is repeated to correct the resistivity of the conductive materials which affect the solution and hence the internal Joule heat generation within the conductors. Finally, the coupled electromagnetic and thermal steady-state diffusion problems have been solved by an iterative procedure, consisting of the following step:

Step “1”: The solution of electromagnetic problem field equations leads to the unknown values of magnetic vector potential $A$ at every node of the 2D finite element model and of the source current density $J_s$ at every conductor. In the first iteration, the temperatures of the conductor materials are set equal to arbitrary and constant values. For all next iterations, the temperature values at every point will be obtained from step “4” and they will be different from point to point. Then the electrical resistivity at every element that lies on the cross-section of the conductor materials is computed.

Step “2”: Using the values of $A$ and $J_s$ from the solution at step “1”, the total element current density $J$ on the cross-section of the conductor materials is computed and the average loss density $q$ at every element of them is calculated.

Step “3”: Using the values of $T$ from the solution in step “4” the thermal map of the model is computed; in particularly, the mean conductor temperatures are calculated.

Step “4”: The solution of the thermal steady-state diffusion problem equation lead to the unknown values of $T$ at every node. The values of $i$ iteration $T_{\mathrm{i}}$ are compared with the values $T$ of the previous iteration. If $| T_{\mathrm{i}} - T \ | \leq \varepsilon$ at every node, where ε is a fixed error, the iterative procedure will be terminated.



## 4 Numerical results

In order to estimate the magnetic pollution due a typical 150 kV underground power cable line laid in urban areas (fig. 1) a parametric analysis has been pointed out.

In particular, the authors have initially compared the performance of a trefoil configuration with respect to a flat configuration (T1 in fig. 1). Assuming as constrain the thermal operating limit of the cables (i.e., $T_M = 85$ °C), a parametric analysis has been pointed out varying the ground surface temperature, $T_{gs}$. For both configurations, when the ground surface temperature increases (from 20 °C to 60 °C), the ampacity of the power line decreases, practically, according to the same linear law (fig. 5). In addition, in all cases studied, the trefoil configuration presents a derating of about 14.5% with respect to the flat configuration; however, at the same time, the maximum values of the magnetic flux density are about 83% lower than that generated by the flat configuration.

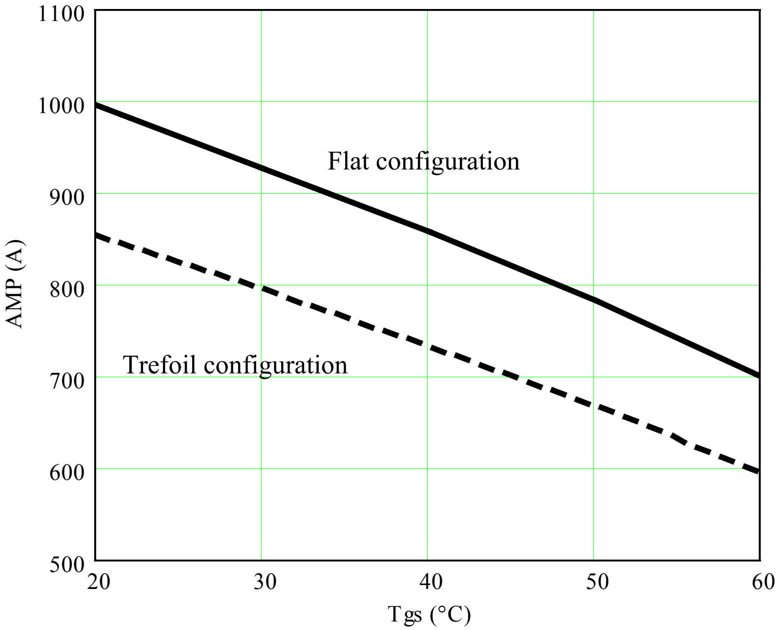
Assuming as constrain the maximum admissible exposure limit (i.e., a magnetic flux density value equal to 3 μT), the current in the single-core cables is considerable influenced by the laid configuration (refer to the configurations T1, T2, T3 and T4 in fig. 1) and, in particular, by the distance between adjacent cables (fig. 6). Instead, the cable ampacity is influenced only by the distance between adjacent cables; in fact, as shown in fig. 7, the laid configuration (with reference to the configurations T1 and T2 in fig. 1) has a negligible influence.

In order to reduce the magnetic pollution due to existing or new installations, the authors, imposing as limitation the maximum admissible operative temperature of the cables, have also investigated the performances of open or closed shields, made of conductive and/or magnetic materials. Some examples of these computations are given in figure 8, where the lateral profile of the magnetic flux density (in p.u.) has been plotted referring to a typical 150 kV underground power line (supplied with a rms current values of 857 A) which has been shielded by open or closed planar screens (having a thickness of 3 mm).

The shields consist of electric conducting material (copper) or magnetic conducting material (iron with BH magnetization curve, see fig. 2). These materials attenuate the low frequency magnetic field, respectively, for eddy current cancellation and flux shunting mechanisms. In order to evaluate the performance of these shields the shielding effectiveness, SE, has been introduced by using

$$SE = 20 \log \left( B_{max} / \underline{B}_{max} \right)$$

In figure 9 the evolutions of the SE versus relative permeability of a closed Fe-shied and an upset U Fe-shield have been plotted. It is interesting to compare the behavior of the closed Fe-shield with the upset U Fe-shield: for the first one the SE always increases as the relative permeability increases while the second one presents a maximum. For the magnetic conducting material (e.g., iron), this behavior is due to the different weight of the two shielding mechanisms (i.e., eddy current cancellation and flux shunting) when the relative permeability increases.



| FLAT CONFIGURATION | | | | | |
|---|---|---|---|---|---|
| $I_{rms}$ (A) | $T_{gs}$ (°C) | $T_{max}$ (°C) | $P_{tot}$ (W/m) | Derating | $B_{max}$ (T) |
| 995 | 20 | 84,25 | 80,47 | *** | 1,37E-05 |
| 927 | 30 | 84,11 | 69,90 | *** | 1,27E-05 |
| 857 | 40 | 84,32 | 59,84 | *** | 1,18E-05 |
| 782 | 50 | 84,65 | 49,91 | *** | 1,07E-05 |
| 698 | 60 | 84,85 | 39,83 | *** | 9,59E-06 |
| **TRIFOIL CONFIGURATION** | | | | | |
| $I_{rms}$ (A) | $T_{gs}$ (°C) | $T_{max}$ (°C) | $P_{tot}$ (W/m) | Derating | $B_{max}$ (T) |
| 853 | 20 | 84,70 | 77,97 | 14,27% | 2,23E-06 |
| 795 | 30 | 84,48 | 67,73 | 14,24% | 2,08E-06 |
| 733 | 40 | 84,42 | 57,59 | 14,47% | 1,92E-06 |
| 667 | 50 | 84,59 | 47,72 | 14,71% | 1,74E-06 |
| 594 | 60 | 84,78 | 37,87 | 14,90% | 1,55E-06 |

Figure 5: Cable ampacity versus ground surface temperatures: comparison between the flat configuration (continuous line) and trefoil configuration (broken line) for the configuration T1 in fig. 1. The ampacity has been calculated in correspondence to the maximum admissible operative temperature of the cables (i.e., $T_M$ = 85 °C).

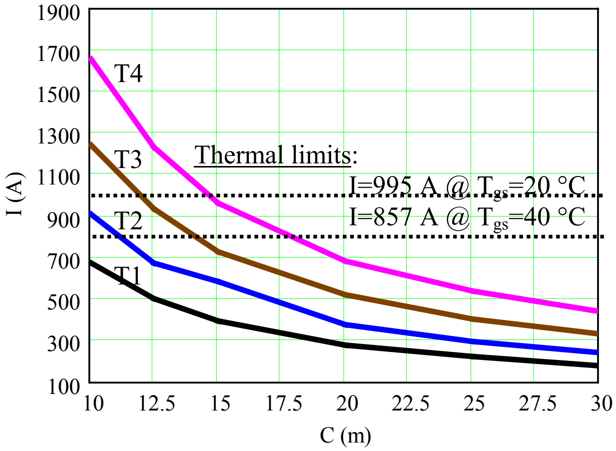


Figure 6: Current flowing through the cables versus distance C between adjacent single-core cables (with reference to the configurations T1, T2, T3 and T4 in fig. 1). In all cases, the values have been calculated imposing as constrain the maximum admissible exposure limit (i.e., a magnetic flux density value equal to 3 μT).

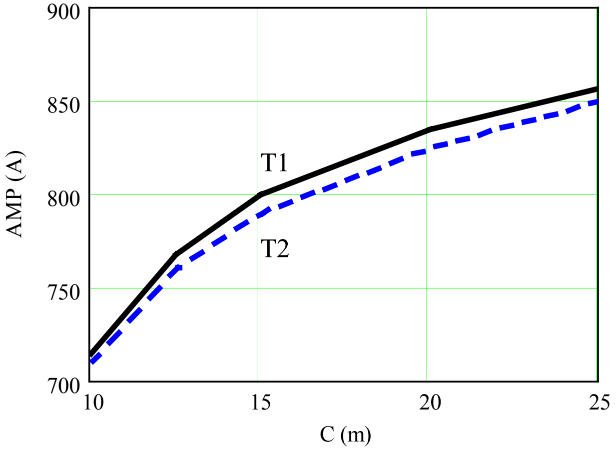


Figure 7: Cable ampacity versus distance C between adjacent single-core cable (with reference to the configurations T1 and T2 in fig. 1). In all cases, the ampacity has been calculated at the maximum admissible operative temperature of the cables (i.e., $T_M$ = 85 °C) and with a ground surface temperature fixed at 40 °C.

The authors have also investigated on how the back-filling thermal conductivity could affect the mean value of the temperature of the middle conductor and of its sheath, as well as, of the right conductor and of its sheath.

All the calculation have been pointed out imposing a balanced rms current of 857 A and a ground surface temperature of 40 °C.

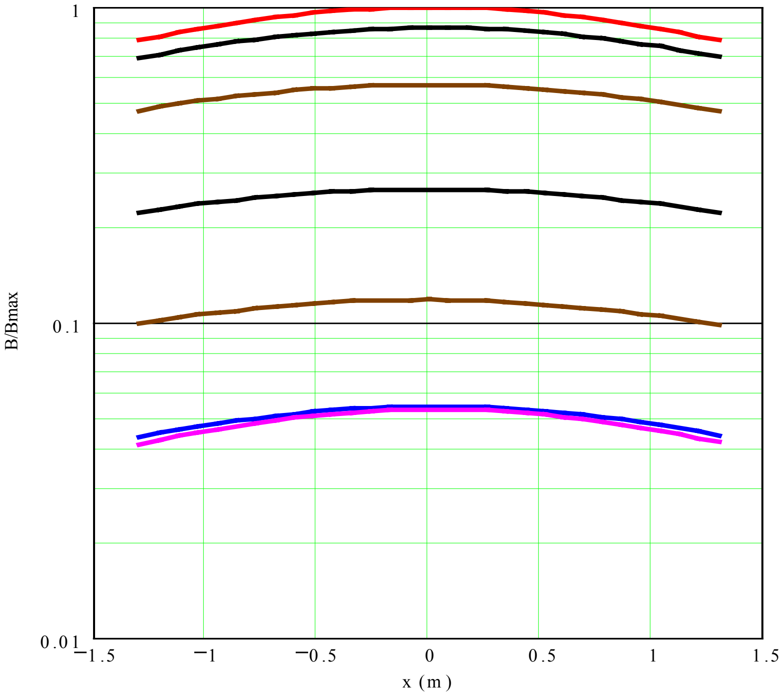


Figure 8: Lateral profile of the magnetic flux density (in p.u.) generated by flat configuration supplied with a rms current values of 857 A, in absence and in presence of planar screens (having a thickness of 3 mm). The shields consist of electric conducting material (copper) or magnetic conducting material (iron with BH magnetization curve, see fig. 2). From the upper line to the lower line, the curves refer to the following shield configurations: no shield, upper Fe-shield, upper Cu-shield, upset U Fe-shield, upset U Cu-shield, closed Cu-shield and closed Fe-shield. The magnetic flux density has been calculated at one meter above the ground surface.

## 5 Conclusions and remarks

In this paper the authors have proposed a parametric analysis of a typical 150 kV underground line in order to evaluate the influence of the effective operating conditions on the magnetic pollution generated by the power cables. The mitigation of the magnetic field, due to flat configurations or trefoil configurations, has been analysed in detail by a coupled electro-magnetic and thermal formulation based on a finite element model (FEM).

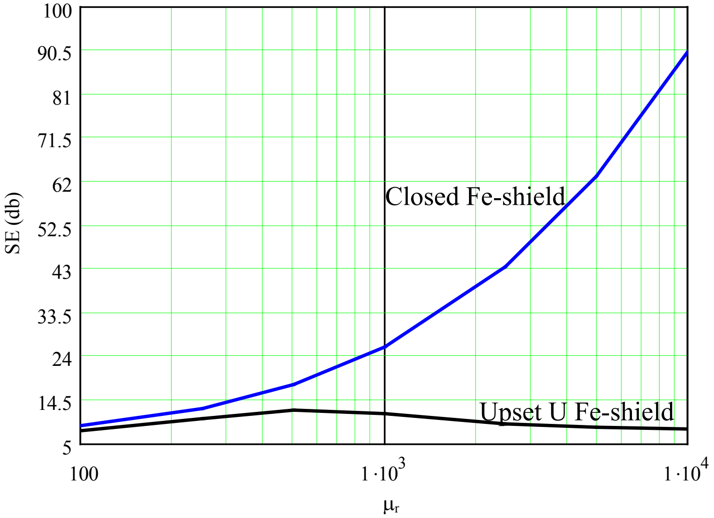


Figure 9: Evolution of the SE versus relative permeability of the shields.

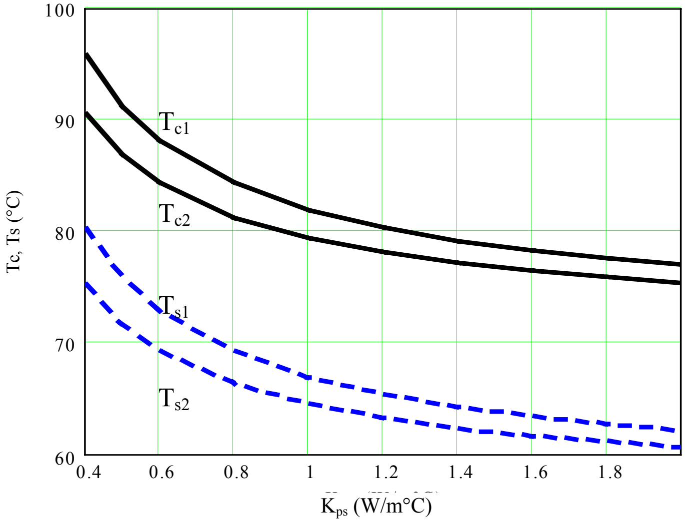


Figure 10: Mean temperatures versus packet sand (or other back-filling) thermal conductivity $K_{ps}$: $T_{c1}$ and $T_{s1}$ refer to the middle conductor (solid lines) and its sheath (dashed lines), while $T_{c2}$ and $T_{s2}$ refer to the right conductor (solid lines) and its sheath (dashed lines). In all investigated cases the temperature has been calculated with cables supplied by a balanced currents of $I_{rms}$ = 857 A (ampacity) and the ground surface temperature set to 40 °C.

This study have had the aim to evaluate possible reclamation of existing installations, or accommodation of new installations, by simple passive shielding technologies such as finite width metal shields (made by ferrous or non-ferrous materials). The proposed formulation has taken into account the real geometrical dimensions and the effective physical characteristics of the involved materials. The magnetic field distribution and the temperature distribution have been calculated. The cable ampacity has been also estimated starting from the temperature distribution, using as limitation the maximum admissible operative temperature of the single-core underground power cables. In addition, always imposing the thermal limit, the performances of open or closed shields, made of conductive and/or magnetic materials, have been also investigated, in order to predict the magnetic pollution due to existing or new installations. The results of all simulations shown that simple solutions (e.g., redefinition of the geometrical configuration or laid condition, as well as, solutions that involve flat shields) can be used in order to reduce the magnetic field levels below the exposure limits fixed by law also when the thermal aspects, related to the effective operating conditions of the power line, have taken into account. Further developments of this research concern the generalization of the proposed model accounting for the effective evolutions in the time domain of the supplied currents (e.g., due to effective load diagrams – daily, monthly and yearly – and/or unbalanced current systems). In addition, the performance of variously composed multi-layer shields will be also analyzed.

## Acknowledgments

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