MAGNETIC FIELD MITIGATION
ABOVE A DOUBLE TREFOIL HV UNDERGROUND POWER LINE

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INTRODUCTION

In the last years the effects on human health as a consequence of the exposure to low frequency (LF) magnetic fields generated by electrical energy transmission, distribution and utilisation systems, were considered by different institutions. Reference levels were indicated in the guidelines issued by the International Commission on Non-Ionising Radiation Protection (ICNIRP) and in the European Council Recommendation of 12 July 1999 [1, 2]. Despite the fact that "...measures with regard to electromagnetic fields should afford all Community citizens a high level of protection; provisions by Member States in this area should be based on a commonly agreed framework, so as to contribute to ensuring consistency of protection throughout the Community"[2], national laws provide a non-homogeneous framework. A decree issued in Italy in July 2003 [3] set the new severe limit of $3\mu T$ *in terms of rms magnetic flux density levels close to new plants.*

This paper refers to the design of mitigation solutions for a new double trefoil 132 kV underground power line. The study aimed at limiting the magnetic line emissions at one metre above the ground to comply the limit above mentioned. The investigation has been carried out in two steps through models developed at IEN, which employ the "thin shield" technique and are able to manage shields with different characteristics (ferromagnetic, pure conductive or both). The first step focused on the conductor management compensation. It can be shown that in a double tern there are only six independent phase configurations. The difference among them, in terms of environmental magnetic flux density values above the line, is considerable. A particular phase configuration reduces the highest magnetic field density levels more than three times with respect to the others, complying the most severe limit settled in Italy, without the use of shields. The second step concerns the area of the cable junctions. In these case, due to the greater distance between the conductors, the phase management is not sufficient to comply the limit above mentioned. So the use of a suitable pure conductive shield was investigated for the purpose. A detailed design description and the analysis of possible solutions are presented in the paper, where the effect of the linkages, among shield parts, is also discussed.

SYSTEM CHARACTERISTICS AND FIELD LEVELS

The double trefoil 132 kV power line under investigation, is constituted by six cables, XLPE insulated, with 105 mm external diameter and 1600 mm^2 conductive area. The regular cable disposition is shown in Fig. 1. The two trefoils are supplied in parallel and the basic hypothesis for the mitigation design was the current balancing in both terns (I = 500 A r.m.s. for each conductor; *current phasorial notation* $R \rightarrow \mathbf{I}_1 = I\angle 0°$, $S \rightarrow \mathbf{I}_2 = I\angle 240°$ *and* $T \rightarrow \mathbf{I}_3 = I\angle 120°$).

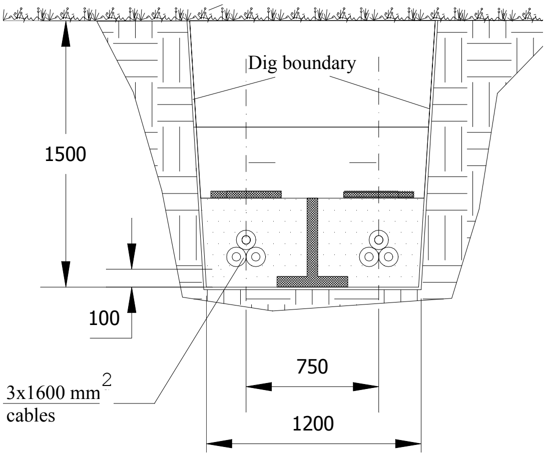

Fig. 1 – Layout of the line. Dimensions in mm

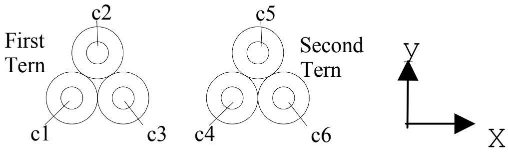

Fig. 2 – Conductor's numeration and reference system axis orientation

The total length of the line is ~1 km. In general, a system with n phases on n conductors can be subjected to $n!$ phase-permutations (6 for a three phase system – three conductors) and so two systems parallel supplied can be subjected to 36 phase-combinations between the sequences of the first tern, called $\boldsymbol{x}$, and the sequences of the second tern called $\boldsymbol{y}$ (see Fig. 2 and Table I). Under the hypothesis of geometric symmetry in the conductor disposition and "triple electric symmetry" (balanced terns of currents), these 36 configurations reduce to only 6 independent phase combinations (IPC), resumed in Table II.

The difference among the IPC, in terms of environmental magnetic flux density values, can be low or high depending on the arrangement of the conductors and on the distance between them [4]. It is evident in Fig. 3α that, in this case, investigating one meter above the ground, the worst configuration (IPC1) produces in the middle of the line a magnetic field 4.4 times higher with respect the best one (IPC2). In absolute terms, this means that maximum rms magnetic flux density levels can be reduced to 1.1 μT one metre above the ground (2.9 μT at ground level). Fig. 3β underlines that the reduction of magnetic flux density between the best and the worst IPC, is not evident only on the resultant rms value, but it is marked also on the rms field components.

When in the junction area the cables of one tern finish, and they have to be bonded with other cables, the conductor distance of the same tern increases, to allow the link execution and practically, the three cables lie on a plane (Fig. 4 α and β). Field levels raise (Fig. 5) and the difference between the IPC becomes less important and, consequently, it is necessary a shield to reduce field levels. The independent phase configurations are defined on the base of symmetry of the system; in the case of junction areas, due to the lack of geometric symmetry, the term IPC is not correct. So, it is better, and more general, to relate the results obtained in junction areas in terms of phase combinations.

Table I. Sequences ***x*** and ***y*** of the two terns

First tern sequence index x			
x	Conductor /phase		
	c1	*c2*	*c3*
1	R	S	T
2	T	R	S
3	S	T	R
4	R	T	S
5	S	R	T
6	T	S	R

Second tern sequence index y			
y	Conductor / phase		
	c4	*c5*	*c6*
a	R	S	T
b	T	R	S
c	S	T	R
d	R	T	S
e	S	R	T
f	T	S	R

Table II. Independent phase combinations **xy**. The combinations disposed in a same row are magnetically equivalent with respect to the magnetic flux density levels above the line

IPC1	1a	2b	3c	4d	5e	6f
IPC2	1b	2c	3a	4e	5f	6d
IPC3	1c	2a	3b	4f	5d	6e
IPC4	1d	2f	3e	4a	5c	6b
IPC5	1e	2d	3f	4b	5a	6c
IPC6	1f	2e	3d	4c	5b	6a

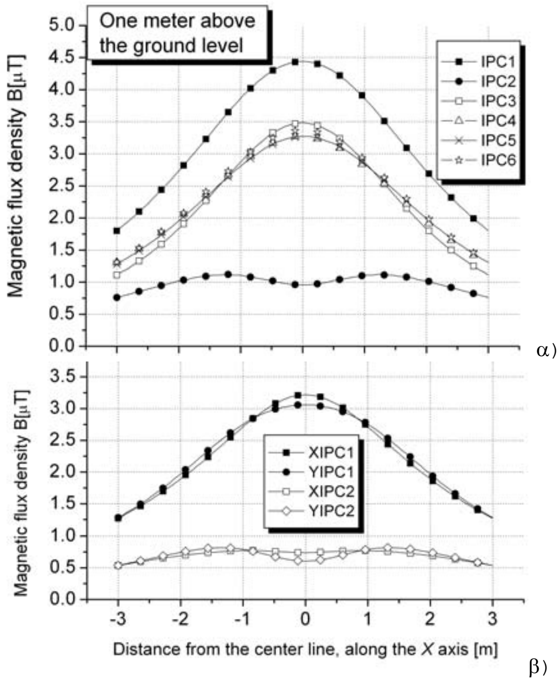

Fig. 3b – α) Magnetic field levels one meter above the ground, with conductors disposed as in Fig. 1 – β) Magnetic flux density components of the IPC1 and IPC2

Cable sheath and grounding system

When a line is longer than one or two kilometres normally it has to be grounded to both extremities (double point bonded). In this case there are actual phase transpositions and so, cross bonds in junction area are generally used in order to limit current circulation within the metallic cable sheaths.

Otherwise, when the line does not exceed one or two kilometres in length, it is possible to avoid cross bonded solutions but, in this case, the line is grounded only to one extremity. This hypothesis has been adopted for the considered line. Under this assumption, the metallic shield and sheath elements of the cables do not have any significant mitigation characteristic. This assumption also avoid actual transposition of the cables in junction areas, though the local one are possible to optimise mitigation (see e.g. Fig. 9).

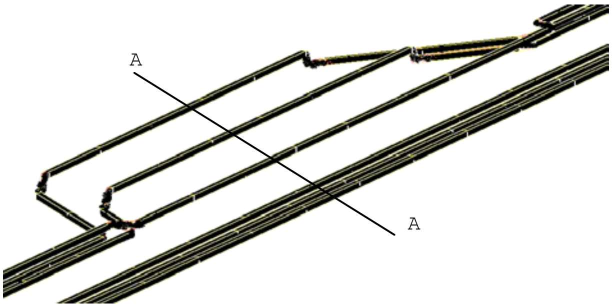

Fig. 4α – Three dimensional representation of the left junction area with an indication of the cross section location of Fig. 4β

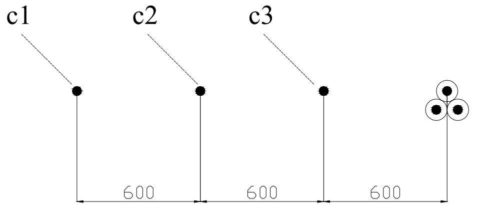

Fig. 4β – Cross-section A-A in the middle of the left junction area. Distance between conductor in mm

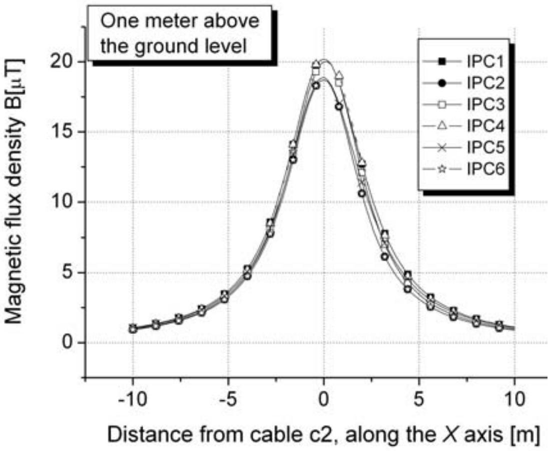

Fig. 5 – Magnetic field levels one meter above the ground; Fig. 4 arrangement

SHIELDING DESIGN

This section deals with the procedure followed in the design of a mitigation solution for the junction area.

The field computation is performed, in this investigation, by means of two numerical codes developed at IEN based on the “thin shield” approach. This technique aims at substituting the three-dimensional shell with a two-dimensional surface imposing suitable interface conditions between the two sides of the surface. This approach is completed with an hybrid FEM-BEM formulation [5,6].

Shield characteristic

The main requirements settled for the shielding system were:

1. magnetic flux density levels one metre above the ground lower than 3 μT;
2. easy accessibility to cables for future maintenance operations;
3. use of 2 mm thick aluminium sheets;
4. shield dimensions related to the ordinary dig width and depth.

The choice of a aluminium shield is due to the fact that it is a good conductor, easy available on the market, with a good resistance to corrosion. Besides, the ferromagnetic materials in sheets and in non-completely close shield arrangement are less effective at a certain distance from the source with respect to conductive materials [7].

Preliminary two dimensional approach

A fast 2D approach based on “thin shield” formulation was followed. Due to requirement 2., above mentioned, complete closed solutions were not considered, except one case for comparison purposes.

Following shielding configurations were considered, where C1-shape and C2-shape are two slightly different C-shape shields:

a) simple plate above the conductors;
b) simple plate below the conductors;
c) C1-shape shield below the conductors;
d) C2-shape shield below the conductors;
e) C1-shape shield above the conductors;
f) C1-shape shield above the conductors with a non welded cap;
g) C2-shape shield above the conductors with a non welded cap;
h) complete close shield.

All the computations were performed using the phase combination 1b (see Tables I, II and Fig. 4) correspondent to the IPC2 for the double trefoil disposition.

Fig. 7 shows how the best shielding performance is due to the close shield, as expected, but also shows how the presence of a simple non welded cap, with a C shape shield seems to be very effective. At any rate, open configurations c) and d) seem to be the most interesting, since they are rather effective and are very convenient for maintenance operations. So, in the following, configuration c) and d) will be considered for a further investigation.

Since we have two trefoils there are two separate junction areas, in general one next to the other one, but separate. In these areas one trefoil continue with its phase sequence and the other one is bonded to its prosecution. In these areas phases can be locally and/or actually transposed. Due to the grounding system choice, only local transposition were considered. We can say “left junction configuration” when the link interests the left trefoil and, vice versa, “right junction configuration” when the link interests the right trefoil.

The best phase combination of the double trefoil line does not correspond to the best one in the junction area in presence of a shield. This is mainly due to the shield presence and it is shown in Fig. 8, in the case of the d) shielding arrangement. It is evident how the difference between the “best” and the “worst” combinations is about 15% without shield (Fig. 5) and become 35% in presence of the shield.

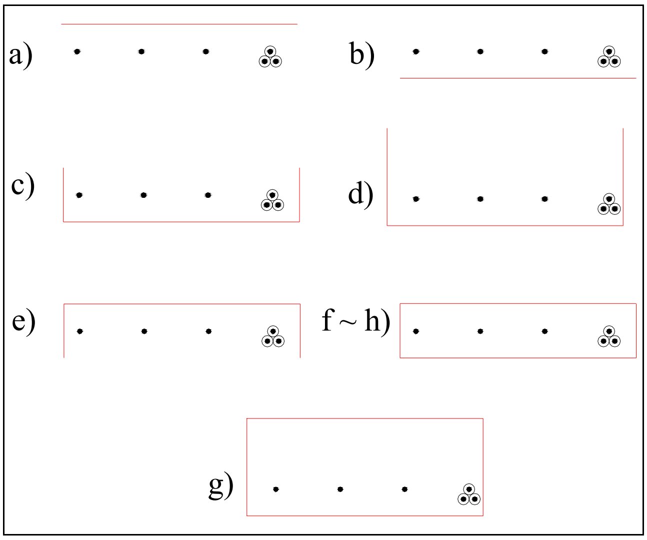

Fig. 6 – Synthesis of the considered shields showed in the left junction configuration. Shield width: 2.2 m. Shield height: 0.5 m or 0.9 m

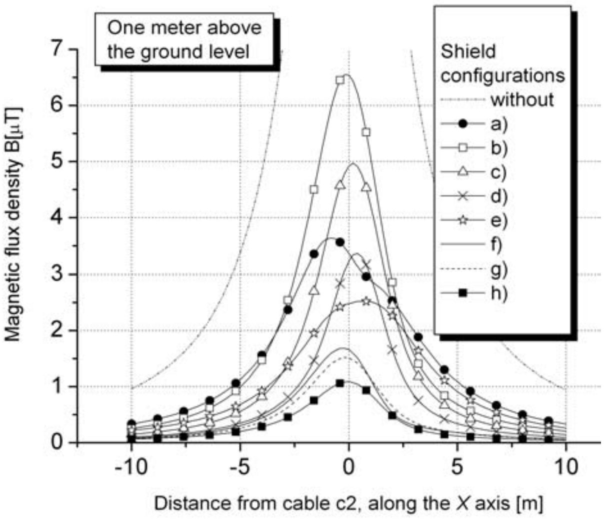

Fig. 7 – Magnetic field levels one meter above the ground in the left linkage area; for the different shield arrangements

Besides, the best phase combination depends on the cable arrangement and this means that the results are quite different between left and right junction configurations. In Fig. 9, for the considered d) arrangement, the necessary local cross links are summarized in order to achieve the best phase management. Moreover, for a same cable layout, the better phase slightly depends on the shield type. So, considering the left junction arrangement, combination 4b is the top for shields c) and d), 4b and 1b are almost the same best combination for f) and g) arrangements, 1b is the better for the complete close shield d) and simple plate b) shield.

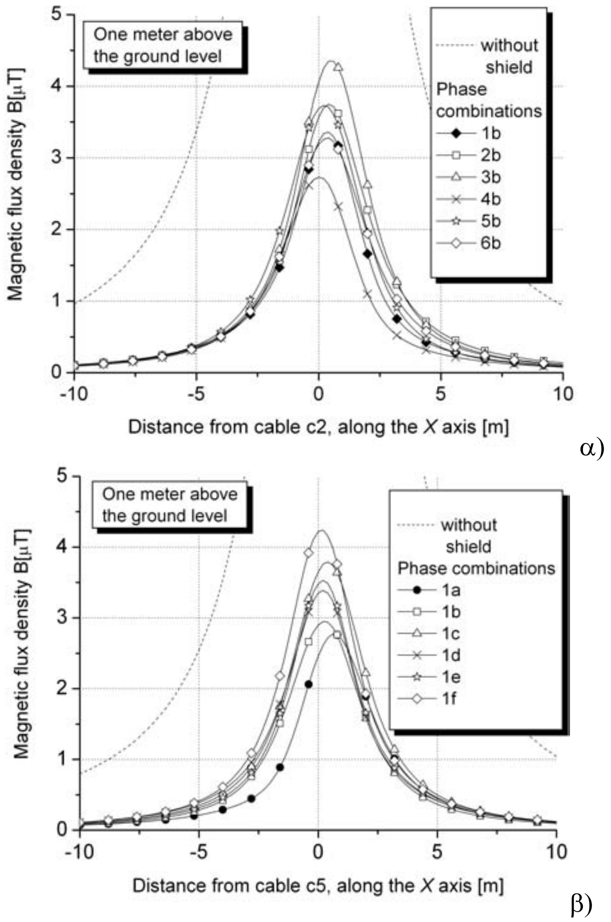

Fig. 8 – Magnetic flux density one meter above the ground in the linkage area, considering the d) shield arrangement; α) left junction arrangement, β) right junction arrangement

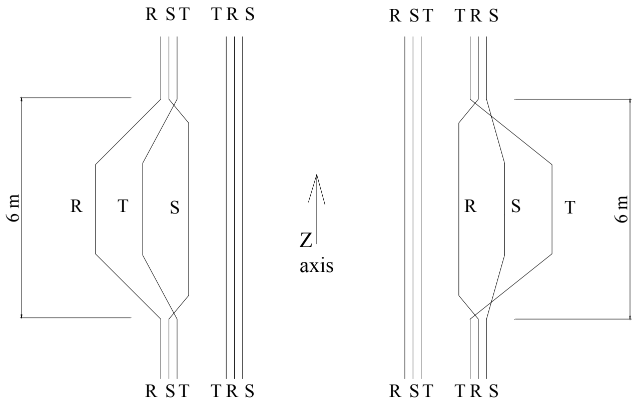

Fig. 9 – Left and right junction configurations and phase sequences that optimise mitigation in configurations c) and d)

Three dimensional approach

A two dimensional approach corresponds to an indefinite shield and cable system as shown in Fig. 10 α). Considering a limited extension of the shield (Fig. 10 β) the problem becomes immediately three dimensional and, in this case, the 2D model underestimates the field levels above the line and neglects the edge effects. On the contrary, if a complete three dimensional approach is followed (Fig. 10 γ), and the shield lies under the link, slightly exceeding the junction area (Fig. 10 δ), the 2D approach overestimate the field levels above the line, both the maximum values in the middle of the shield and the edge values, where the cables are closer together.

As an example, Fig. 11 shows the effects of the 3D approach and of the phase combination 4b in the linkage area, the for the c) shield, left junction arrangement; the mitigation improvement in comparison to Fig. 7 is evident.

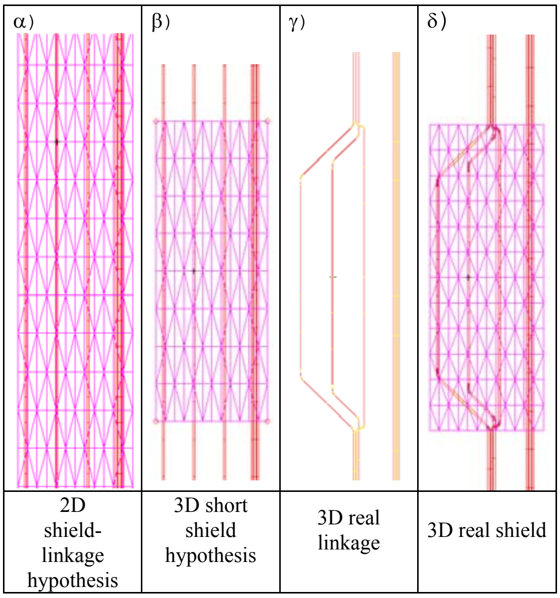

Fig. 10 – Different approaches for linkage investigation

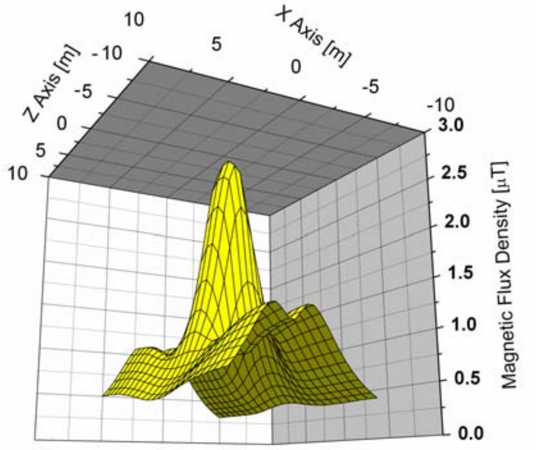

Fig. 11 – Magnetic field levels one meter above the ground, left junction area, c) shield configuration. Z axis is the line axis (see Fig. 9) – From 7 metres before to 7 meters after the shield

EFFECT OF SHIELD PART LINKAGES

Until here, three dimensional computations were performed with a whole C shape shield without air gaps. This hypothesis can be partly correct, since the dimensions of the commercial sheets allow to bend the metal in C shape, but normally it is impossible to reach the necessary shield length. To complete the example in Fig. 11, three sheets 2 m long, bent in c) shield configuration, were supposed placed close together to achieve a six meter long shield. The three shield parts were imagined linked by two stripes 2 mm thick. The stripes were supposed with different values of electrical conductivity, from zero (negligible) to 30 MS/m, the usual conductivity of aluminium sheets. The results were computed one metre above the line, in correspondence to the conductor c2, for twenty meters along the line, starting 7 metres before the shield and ending 7 metres after. These results are presented in Fig. 12. The same computation was carried out at the ground level and results are summarized in Fig. 13.

Diagrams put in evidence how the mitigation capability of the shield strongly decreases whit the reduction of the electric conductivity between the shield parts which are disposed along the line. This one, can be defined general effect. Moreover there is another local effect, more evident going towards the source (Fig. 13), which consists of local magnetic flux density peaks above the link stripes. The more the stripe conductivity is low, the higher are local induction peaks. These results, obtained for the C-shape shield, can be extended to the other considered shields.

For the examined line, the preparation in a workshop of shields constituted by three bent aluminium sheets, welded with TIG technique one to the other, and the transport of shields six meters long, don't represent a difficulty in the shielding system achievement.

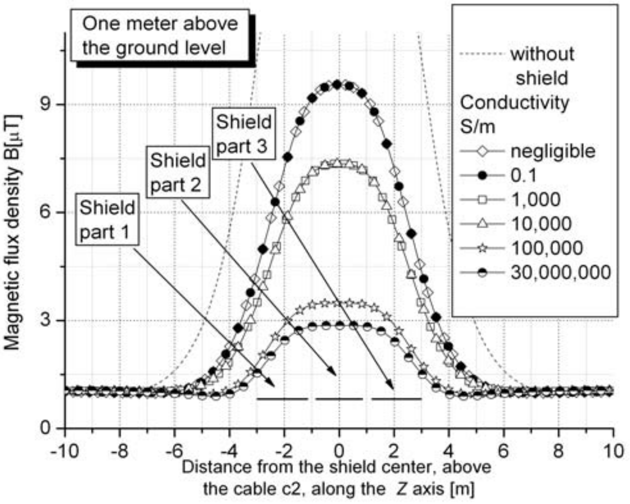

Fig. 12 – Magnetic field levels one meter above the ground, left junction area, c) shield configuration. Z axis is the line axis (see Fig. 9)

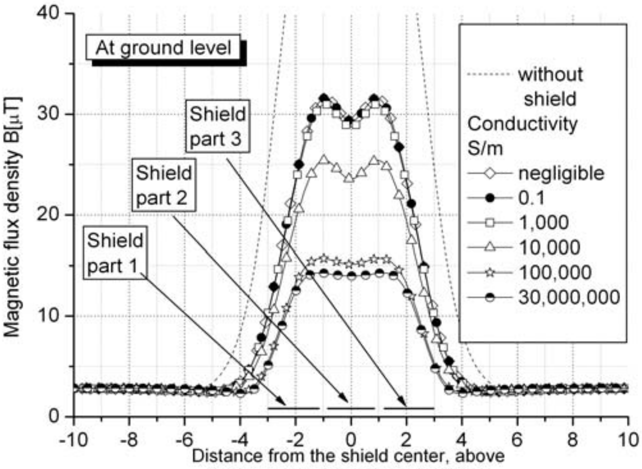

Fig. 13 – Magnetic field levels at ground level, left junction area, c) shield configuration. Z axis is the line axis (see Fig. 9)

CONCLUSIONS

This investigation dealt with the mitigation of magnetic field levels above a due double trefoil line. It was evidenced how phase management compensation can be a very important mitigation solution, for the double trefoil disposition considered. Under the hypothesis of line grounded only to one extremity, metallic shield and sheath elements of the cables don't have any significant mitigation characteristic.

Nevertheless, magnetic field levels produced in correspondence of the cable joints, where conductors are more distant, suggest the use of shields in that area. In this study non completely-close shields, made with common aluminium sheets, were considered. The design evidenced how the best phase sequence, which means that minimise the magnetic field above the line, for the same cable arrangement depends on the presence of conductive (and/or ferromagnetic) materials around the line; so it varies depending on the presence of the shield. For this reason cross bonds with local cables transposition can be used to optimise mitigation.

Besides, the limits of a 2D design approach were put in evidence using a three dimensional numerical code. It was evidenced also the importance of a good welding, with more or less the same electrical conductivity of the aluminium, between the shields parts disposed along the line, to make significant the results obtained with the 2D hypothesis and with a simplified 3D approach.

Acknowledgments

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REFERENCES

[1] ICNIRP, 1998, "Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz), Health Physics.
[2] COUNCIL OF THE EUROPEAN UNION, 1999, "Council Recommendation on the limitation of exposure of the general public to electromagnetic fields (0 Hz – 300 GHz)". (1999/519/CE).
[3] Decreto della Presidenza del Consiglio dei Ministri 2003 (8 luglio), GU n.199 e n. 200 del 28/29 Aug 2003.
[4] O. Bottauscio, M. Chiampi, R. Conti, M. Repetto, M. Zucca, 2000, "Some considerations about environmental ELF magnetic field reduction", Brugge (Belgium), EMC Europe, Tutorial Session n. 6, pp. 112-121
[5] I. Mayergoyz, , 1998, "Nonlinear diffusion of electromagnetic fields", Academic Press
[6] O. Bottauscio, M. Chiampi, A. Manzin, 2003, "Numerical analysis of magnetic shielding efficiency of multilayered screens", IEEE Trans. on Magn., 40, 2, 726
[7] O. Bottauscio , M. Chiampi, D. Chiarabaglio, F. Fiorillo, L. Rocchino, M. Zucca, 2001, "Role of magnetic materials in power frequency shielding: numerical analysis and experiments", IEE Proc. Generation, Transm. and Distribution, Vol. 148, pp. 104