Exposure reduction and containment, predictive calculations and shielding[1]

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1. Introduction

The need to reduce the intensity of the electromagnetic field present in a given region arises in various situations. Containing the exposure of individuals within levels deemed safe and avoiding interference with sensitive electronic devices are certainly the most typical cases. In this document, we shall mainly refer to the first of these cases, although many of the considerations developed are easily applicable to problems of electromagnetic compatibility between devices as well.

To address these problems, one must start by recognising the role of two main actors: the source that generates the electromagnetic field, and the victim that is located in the controlled region and whose exposure one wishes to decrease. For the solution, three different strategies are available. One can act on the source, reducing its intensity or modifying other emission characteristics; or one can move the source away from the region to be protected; finally, specific devices can be used that are able to reduce the intensity of the field by acting on the electromagnetic coupling between the source and the victim. We shall generically call these devices shields, and shielding the technology related to their use.

In the first part of this document some general concepts underlying shielding methods will be illustrated. In the second, we shall deal in particular with the exposure reduction methods applicable to the emissions of extra-high-voltage power lines.

2. When is it necessary to adopt an exposure containment technique?

Two attitudes can be adopted towards this problem: a radical attitude and a rational attitude. Those who adopt the former consider the electromagnetic field an element foreign to the environment, hence unwanted, and advocate adopting in any case whatever reduction measure is available, regardless of the field values at play. Those who lean towards a more rational approach require that thresholds be identified below which the field values can be considered safe; in this case, reduction measures will be adopted only at those sites where a preliminary assessment has predicted values above the preset thresholds.

Although the radical approach may seem appealing, being apparently able to provide the maximum possible protection, it turns out to be less attractive if one considers that the resources invested in an unnecessary intervention (hence one that brings no certain benefit in health terms) will have to be diverted from other sectors, where perhaps they could have achieved better results.

The main problem connected with the adoption of a rational attitude lies instead, as can easily be guessed, in the definition of the threshold values. The preferential reference should obviously be constituted by national and international safety standards. There are, however, differing opinions, supported above all by some environmentalist and consumer protection organisations, according to which the values proposed by the standards do not sufficiently protect the population, since they do not take due account of the possible risk associated with chronic exposure to very low-level fields.

Part one: the shielding of the electromagnetic field[2]

3. Shielding effectiveness

Shielding effectiveness is a figure of merit that quantitatively expresses the ability of a shield to reduce the intensity of the electromagnetic signal reaching a given point; it is customary to use for this quantity the logarithmic formulation in decibels (dB) and the symbol SE_{dB} (from shielding effectiveness). In particular, the shielding effectiveness with respect to the electric field is defined by the relation:

$$\mathrm{SE}_{\mathrm{dB}} = 20\log_{10}\left(\frac{E_1}{E_2}\right) \tag{1}$$

where E_1 is the amplitude of the electric field measured at a predetermined point, before the positioning of the shield, and E_2 is the amplitude of the electric field measured at the same point, after the positioning of the shield.

The shielding effectiveness with respect to the magnetic field and to the power density of the radiation can be defined in an analogous way.

4. What to shield

Generally speaking, shielding realised by means of closed enclosures is more effective than that based on partial shields, although in both cases the actual performance is significantly degraded by the presence of apertures.

The conceptually preferable approach is to enclose the whole source in a closed container, because in this way every inconvenience or limitation resulting from the application of the shield falls on the source itself. However, this approach is not always feasible. It certainly is not if we are dealing with an intentional broadcasting source (such as, for example, a telecommunications transmitter), because the shielding would make it impossible to deliver the service for which the source is intended. Conversely, shielding the source can be a viable approach in the case of unintentional sources (whose emission is not functional to the service performed: think for example of a household appliance) and also in the case of intentional sources with localised

2. This part is a synthesis of some sections of the chapter "La schermatura dei campi elettromagnetici" ("The shielding of electromagnetic fields"), by D. Andreuccetti and C. Riminesi, in "La schermatura dei campi elettrici, magnetici ed elettromagnetici: principi generali, aspetti teorici e applicazioni pratiche", Franco Angeli Editore, Milan 2006, edited by Paolo Bevitori.

emission, whenever it is possible to enclose within the shield, besides the source, also the whole region in which it performs its task. A typical example of the latter situation is the microwave oven.

When the complete shielding of the source is not technically practicable, the second option to consider should be the complete shielding of the victim. If there are economic reasons, or unacceptable limitations to the usability of the areas to be protected, that advise against adopting this second option as well, one must resort to the interposition of partial shields (plates) or to the use of devices of another type, capable of knocking down the intensity of the field.

5. The ideal shield

We now present a simple theoretical model capable of describing the behaviour of an ideal shield and of assessing its shielding effectiveness. The model is based on the analysis of the phenomena occurring when a plane electromagnetic wave impinges perpendicularly on the surface of the shield, consisting of an indefinitely extended homogeneous flat plate, having uniform thickness t and made of metallic material or in any case a good conductor. The plate separates two half-spaces, one containing the source, the other containing the victim. The wave striking it is partly reflected at the air-conductor interface and partly transmitted into the shield. Reflection is to all intents and purposes a shielding mechanism, since the power associated with the reflected wave does not reach the victim, as it would instead in the absence of the shield. Associated with this mechanism is a first reflection loss, for which we shall use in the following the symbol $R^{(1)}$_dB to indicate its numerical value expressed in decibels.

The wave transmitted inside the shielding material undergoes an attenuation while propagating in it; associated with it is an absorption loss, for which we shall use the symbol A_{dB}.

Finally, having reached the vicinity of the conductor-air interface, the wave undergoes a second reflection and only a part of it is transmitted beyond the shield, towards the victim; we shall denote by the symbol $R^{(2)}$_dB the extent of the second reflection loss.

The second reflection may be followed by subsequent reflections on the two discontinuity surfaces. These lead to a worsening of the shielding effectiveness, which we shall express quantitatively by the term B_{dB}, whose value is always negative.

Ultimately, it is possible to regard the shielding effectiveness of an indefinite flat plate as the result of the superposition of the contributions of four main action mechanisms, linked respectively to the reflection on the first discontinuity surface (air-metal), to the absorption within the metal thickness, to the reflection on the second discontinuity surface (metal-air) and to multiple reflections. In formulas we shall have:

$$\mathrm{SE}_{\mathrm{dB}} = R^{(1)}_{\mathrm{dB}} + A_{\mathrm{dB}} + R^{(2)}_{\mathrm{dB}} + B_{\mathrm{dB}} \tag{2}$$

We shall now analyse quantitatively the phenomena described above, limiting ourselves for brevity to reporting the main results, i.e. the mathematical expressions for the terms of equation (2), capable of linking the shielding effectiveness to the characteristic parameters of the problem.

Let us therefore consider a linearly polarised plane wave, normally incident on the separation surface between the medium of origin (medium 1, which we shall assume to be air or vacuum) and the medium constituting the shield (medium 2, which we shall assume to be a metallic material).

5.1 Shielding effectiveness due to the reflections on the discontinuity surfaces

From the way the problem has been formulated, it is evident that the electric field and the magnetic field are parallel to the discontinuity surfaces introduced by the shield. On the other hand, starting from the general equations of the electromagnetic field (Maxwell's equations) written in integral form, it is possible to show [1, par. 3-6, 6-9, 10-16] that the tangential components of the fields are preserved when crossing a discontinuity surface. If we recall that each electric component is linked to the corresponding magnetic component through the wave impedance, and denote by ζ_1 the wave impedance in the first material (the medium of origin) and by ζ_2 the one in the second material (the shield), one arrives in a few steps at showing that the contribution to the shielding effectiveness with respect to the electric field due to the first reflection at the air-metal interface is given by:

$$R_{\mathrm{dB}}^{(1)} = 20\log_{10}\left(\frac{\zeta_1+\zeta_2}{2\zeta_2}\right) \tag{3}$$

With a similar procedure, for the magnetic field one finds:

$$R_{\mathrm{dB}}^{(1)} = 20\log_{10}\left(\frac{\zeta_1+\zeta_2}{2\zeta_1}\right) \tag{4}$$

An analogous reasoning can be applied to the second interface (metal-air), obviously exchanging the roles of the terms ζ_1 and ζ_2. One therefore finds:

$$\begin{aligned} R_{\mathrm{dB}}^{(2)} &= 20\log_{10}\left(\frac{\zeta_2+\zeta_1}{2\zeta_1}\right) \text{ for the electric field} \\ R_{\mathrm{dB}}^{(2)} &= 20\log_{10}\left(\frac{\zeta_2+\zeta_1}{2\zeta_2}\right) \text{ for the magnetic field} \end{aligned} \tag{5}$$

where the assumptions have been implicitly adopted that the wave impedance in the first material is the same on both sides of the shield, and that the reflections on both surfaces can be described in terms of a transition between two indefinite homogeneous half-spaces. It can be shown that these schematisations lead to determining an upper bound for the shielding effectiveness. The overall contribution R_{dB} to the shielding effectiveness due to the two main reflections on the first and second discontinuity surfaces is ultimately:

$$R_{\mathrm{dB}} = R_{\mathrm{dB}}^{(1)} + R_{\mathrm{dB}}^{(2)} = 20\log_{10}\left[\frac{(\zeta_1+\zeta_2)^2}{4\zeta_1\zeta_2}\right] \tag{6}$$

It turns out to be equal for the electric field and for the magnetic field: this identity is a consequence of having schematised the interaction of the field with the surface of the shield in terms of a plane wave and, above all, of having imposed that the wave impedance be equal on the two sides of the shield. We shall see later how to remove this limitation, which is unacceptable at extremely low frequencies.

To use the expressions found, we evidently need to express the value of the wave impedance in the two media as a function of the parameters of the problem and of the dielectric characteristics of the materials involved.

5.2 The wave impedance in the dielectric on the two sides of the shield

The wave impedance ζ_1 in medium 1, which fills the space on the two sides of the shield (and which we assumed to be air or vacuum), depends in a relevant way only on the distance of the source from the surface of the shield, related to the wavelength of the field. The form of this dependence is in general quite complex, being a function of the technical characteristics of the source; in particular, one must distinguish electric-type sources (with an open structure, seats of high potential differences and low currents, which generate in their vicinity a field in which the electric component prevails) from magnetic-type sources (with a closed structure, seats of low potential differences and high currents, which generate in their vicinity a field in which the magnetic component prevails). Relations useful for the purposes of this treatment can be derived by studying the behaviour of the field generated by particularly simple sources, such as elementary dipoles. This analysis can be found in many textbooks [1, par. 14-3, 14-12]; here we limit ourselves to recalling its main results in schematic form, for a general framing, and to a summary description of what happens.

The parameter to which it is appropriate to refer in order to compare the distance r between source and shield with the wavelength λ turns out to be the quantity λ/2π. If the distance r is greater than this quantity, then the electromagnetic field incident on the shield has the characteristics of the plane wave in free space. For distances r smaller than the indicated parameter, the wave impedance tends to grow linearly as one approaches electric-type sources, and tends to decrease proportionally to the distance for magnetic-type sources. One must not think, however, that by getting sufficiently close to a source it is possible to experience arbitrarily large or arbitrarily small field impedances. In reality, it can be shown that the wave impedance never rises above, nor falls below, the value corresponding, to a first approximation, to the internal impedance of the source ζ_S. However, since this value is not always known or estimable, this limitation is often ignored.

Ultimately, the behaviour of the wave impedance ζ_1 in air or vacuum, as a function of the distance r from an elementary source operating at frequency f (and hence with wavelength λ = c/f, where c is the phase velocity equal, as is well known, to about 3×10^8 m/s) and characterised by an internal impedance ζ_S, is schematically illustrated in Table 1 (relating to electric sources) and in Table 2 (for magnetic sources). In these tables, ε_0 and μ_0 are the absolute electric permittivity and magnetic permeability of empty space, while the quantity ζ_0 (called the intrinsic impedance of empty space) is worth about 376.7 Ω; ε and μ are the absolute electric permittivity and magnetic permeability of the (metallic) material constituting the shield.

Table 1. *Wave impedance in air or vacuum, as a function of the distance r from an electric-type source (internal impedance ζ_S greater than the intrinsic impedance of empty space ζ_0).*

Distance from the source r	Wave impedance ζ_1
$r \geq \lambda/2\pi$	$\zeta_1 = \zeta_0 = \sqrt{(\mu_0/\varepsilon_0)}$
$(\lambda/2\pi)\cdot(\zeta_0/\zeta\_S) \leq r \leq \lambda/2\pi$	$\zeta_1 \approx [\lambda/(2\pi r)]\cdot\zeta_0$
$r \leq (\lambda/2\pi)\cdot(\zeta_0/\zeta\_S)$	$\zeta_1 \approx \zeta\_S$

Table 2. *Wave impedance in air or vacuum, as a function of the distance r from a magnetic-type source (internal impedance ζ_S smaller than the intrinsic impedance of empty space ζ_0).*

Distance from the source r	Wave impedance ζ_1
$r \geq \lambda/2\pi$	$\zeta_1 = \zeta_0 = \sqrt{(\mu_0/\varepsilon_0)}$
$(\lambda/2\pi)\cdot(\zeta\_S/\zeta_0) \leq r \leq \lambda/2\pi$	$\zeta_1 \approx [2\pi r/\lambda]\cdot\zeta_0$
$r \leq (\lambda/2\pi)\cdot(\zeta\_S/\zeta_0)$	$\zeta_1 \approx \zeta\_S$

5.3 The wave impedance in the material constituting the shield

To determine the value of the wave impedance ζ_2 in the second medium, the one constituting the shield, one must consider how the electromagnetic field propagates in it; these considerations will then be useful also to determine the contribution A_{dB} to the shielding effectiveness due to the absorption undergone by the wave in crossing it. To this end, one must start from the system of Maxwell's equations in the differential formulation valid in a homogeneous, source-free material endowed with absolute electric permittivity ε, absolute magnetic permeability μ and electric conductivity σ. The general solution of the system in question, in a sinusoidal harmonic regime with frequency f and angular frequency ω = 2πf, turns out to consist of an electromagnetic wave that attenuates exponentially while propagating inside the metallic material. The amplitude of the wave as a function of the penetration x is indeed given by:

$$E(x) = E_0 \exp\left(-\frac{x}{\delta}\right) \tag{7}$$

where E_0 is the value of the field amplitude at the air-metal interface and:

$$\delta = -\frac{1}{\Im(k)} \tag{8}$$

with:

$$k^2 = -j\omega(\sigma + j\omega\varepsilon)\mu \tag{9}$$

The quantity δ has the dimensions of a length, represents the depth at which the amplitude of the field is reduced to a fraction equal to 1/e of its value at the moment of entry into the shield, and is called the penetration depth of the electromagnetic field into the shield; working a little on equations (8) and (9), its expression can be derived in the case of metallic materials or in any case good conductors (for which $\sigma >> \omega\varepsilon$), as the materials of which electromagnetic shields are made normally are. One finds:

$$\delta \approx \frac{1}{\sqrt{\pi f \sigma \mu}} \tag{10}$$

Table 3. *Barrier impedance of a flat shield, as a function of its thickness t and of the electromagnetic characteristics of the material constituting it.*

Thickness t	Barrier impedance ζ_2
$t >> \delta$	$\zeta_2 \approx \sqrt{2}/(\delta\sigma) \approx \sqrt{(\omega\mu/\sigma)}$
General case	$\zeta_2 \approx \sqrt{2} / [\delta\sigma\cdot(1 - e^{(-t/\delta)})] \approx \sqrt{(\omega\mu/\sigma)} / (1 - e^{(-t/\delta)})$
$t << \delta$	$\zeta_2 \approx (\delta/t)\cdot\sqrt{(\omega\mu/\sigma)} \approx \sqrt{2}/(t\sigma)$

Starting from the same basic equations, it is also possible to derive the expression of the wave impedance ζ_2, called the barrier impedance of the shield, as a function of its thickness t and of the electromagnetic characteristics of the material constituting it; assuming again that this is metallic (a good conductor), one arrives at the situation described in Table 3, where equation (10) has also been used to introduce the penetration depth δ.

5.4 Shielding effectiveness due to absorption in the metal

The expression provided by equation (7) for the amplitude of the electric field inside the shielding material as a function of the penetration x makes it easy to compute how much the wave attenuates in crossing the whole thickness t of the shield, and hence to determine the parameter A_{dB} characterising the absorption losses in the material. It is not difficult to find that:

$$A_{\mathrm{dB}} = 20 \log_{10} \left(e^{\frac{t}{\delta}} \right) = 20 \frac{t}{\delta} \log_{10} e \approx 8.686 t \sqrt{\pi f \sigma \mu} \tag{11}$$

5.5 Degradation of the shielding effectiveness due to multiple reflections

As mentioned, the multiple reflections inside the plate-shield lead to a degradation of the shielding effectiveness. Indeed, a part of the wave reflected back at the second discontinuity surface (metal-air) can still manage to reach the victim thanks to a new reflection on the first discontinuity surface; further multiple reflections can bring other contributions to the field reaching the victim.

However, the contributions due to multiple reflections have undergone — compared with the main contribution — at least two more crossings of the shield, with the consequent attenuations due to absorption in it. It is therefore legitimate to expect their contribution to be negligible, unless the shield has a very low absorbing power (measured by the parameter A_{dB}). As a practical rule, it is generally considered that the contribution of multiple reflections is negligible if A_{dB} ≥ 15 dB. Otherwise, the value of the shielding effectiveness must be corrected, taking into account also the term B_{dB}; without being able to go into details here, it can be shown that to a first approximation:

$$B_{\text{dB}} \approx 20\log_{10}\left|1 - e^{-(1+j)\frac{2t}{\delta}}\right| \tag{12}$$

At this point one has available, albeit deduced on the basis of a rudimentary and at times not completely rigorous theoretical model, all the elements needed to characterise the operation of a flat shield in the various operating situations. In the next section we shall see how to apply in practice, i.e. to the solution of real problems, the knowledge acquired so far.

5.6 Application procedure and general remarks

It is first of all worth keeping in mind that no real shielding problem can be solved entirely theoretically, especially if the theory is based on a simplified model like the one just presented. The theoretical model must be considered only a useful tool for a first assessment of the problem. The practical application of the model typically goes through the following steps.

One must first of all establish whether the source is of the electric type (i.e. a seat of high potential differences and low currents, with high internal impedance ζ_S) or of the magnetic type (a seat of low potential differences and high currents, with low internal impedance ζ_S). One should also, if possible, estimate the internal impedance ζ_S of the source.

It is then necessary to determine the frequency f and the wavelength λ at which the source emits and the distance r between the source and the position of the shield. With these parameters, it is possible to determine the wave impedance ζ_1 in the medium outside the shield, referring to Table 1 for electric sources and to Table 2 for magnetic sources.

Finally, it is necessary to obtain the electric conductivity σ, the absolute magnetic permeability μ and the thickness t of the shield, so as to be able to compute the penetration depth δ (equation (10)) and the wave impedance ζ_2 (Table 3) in it. For this purpose, Table 4 may prove useful, reporting the characteristics of the metals most commonly used for shielding.

Table 4. *Typical values of the conductivity σ and of the absolute magnetic permeability μ of the metals commonly employed for shielding.*

Metal	Conductivity σ (MS/m)	Absolute magnetic permeability μ (μH/m)
Copper	58.0	1.26
Gold	40.6	1.26
Aluminium	34.8	1.26
Zinc	17.4	1.26
Iron	9.86	1260 (at low frequency)
Mumetal	1.74	100000 (at low frequency)

At this point all the parameters needed to compute the shielding effectiveness with relations (2), (6), (11) and, if necessary, (12) are available.

Note that iron, having a conductivity equal to about 1/6 of that of copper, but a magnetic permeability 1000 times greater, ends up having — at the same frequency — a penetration depth about 13 times smaller than that of copper and a barrier impedance almost 77 times greater. This makes iron more effective than copper, both as regards the absorption mechanism and — for some combinations of thicknesses and distances from the source — as regards the reflection of the low-impedance field, i.e. of the magnetic field. All this, however, applies only at relatively low frequencies (up to a few tens of kilohertz at most), because as the frequency rises, the permeability of ferromagnetic materials tends to decrease: above 1 MHz most of them have a relative permeability practically equal to 1.

5.7 Extremely low frequency sources

As we have already had occasion to observe, the theory presented does not meet expectations when applied to extremely low frequency fields, for example to the fields of power lines. It is well known, in fact, that any real shield is very effective in knocking down the electric field and, instead, rather ineffective against the magnetic field. A theory that, for a given source and a given shield, provides the same shielding effectiveness with respect to both components of the field is therefore unacceptable. This situation is a consequence of the model underlying the theory, which is based on the reflection of a plane wave constrained to keep the same wave impedance on the two sides of the shield.

The artifice that makes it possible to use the theory even at extremely low frequencies and to obtain predictions in reasonable agreement with experience consists in considering the real source (for example: a power line) as the superposition of two independent virtual sources: a source of pure electric field (infinite impedance), through which to assess the shielding effectiveness with respect to, precisely, the electric field, and a source of "pure" magnetic field (zero impedance), with which to establish the shielding effectiveness with respect to this second physical agent.

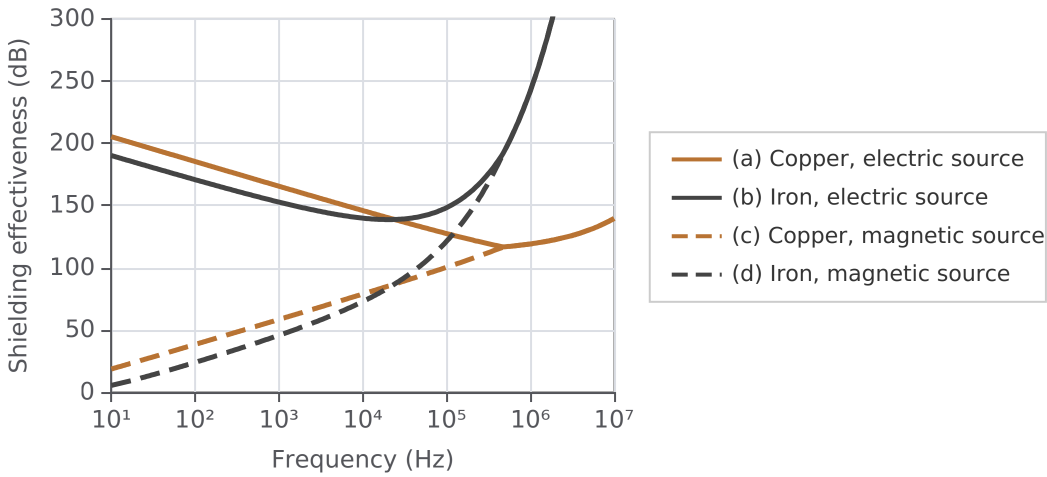

Figure 1. *Shielding effectiveness of a copper plate (lines (a) and (c)) or of an iron plate (lines (b) and (d)) as a function of frequency from 10 Hz to 10 MHz. The plate has a thickness of 0.1 mm and is located 100 m from a source of electric field (lines (a) and (b)) or of magnetic field (lines (c) and (d)).*

5.8 Considerations and examples

It is not easy to discuss in general the behaviour of the shielding effectiveness as a function of frequency, owing to the large number of parameters at play: the electromagnetic properties of the material of which the shield is made, its thickness, the distance from the source, the characteristics of the latter. Some general considerations can be developed with reference to Figure 1 and Figure 2, built on the basis of the procedure outlined above and with reference to the conditions specified in the respective captions.

The first thing that catches the eye is the ease with which very high values of the shielding effectiveness SE_{dB} can be obtained at the frequencies at which the field is radiative (above about 500 kHz, in the case of the example), especially with iron, advantaged by a high value of the magnetic permeability, which abundantly compensates for the lower electric conductivity.

At lower frequencies, i.e. in a reactive field regime, excellent values of the shielding effectiveness are still obtained only for the electric field, while the magnetic field turns out to be more difficult to shield.

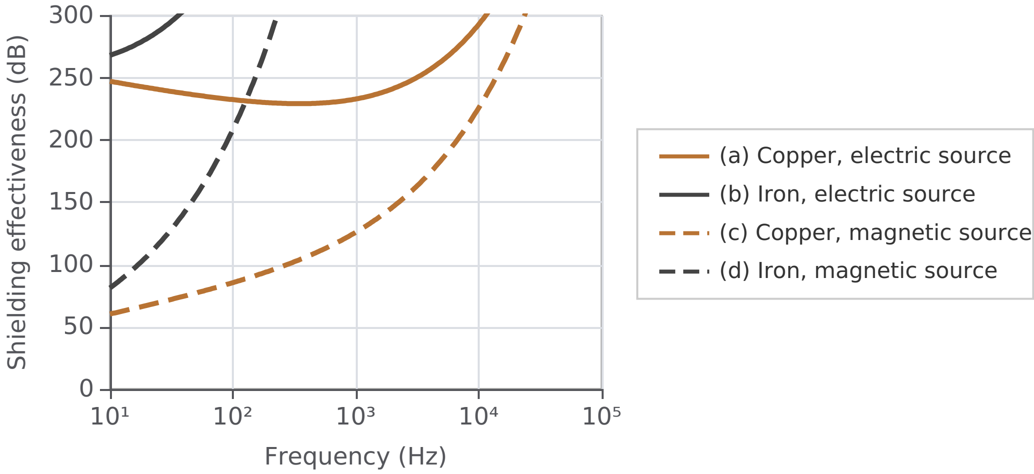

Figure 2. *Shielding effectiveness of a copper plate (lines (a) and (c)) and of an iron plate (lines (b) and (d)) as a function of frequency from 10 Hz to 100 kHz. The plate has a thickness of 1 cm and is located 100 m from a source of electric field (lines (a) and (b)) or of magnetic field (lines (c) and (d)).*

6. Degradation of the shielding effectiveness due to apertures

The shielding effectiveness of an ideal shield is, in many cases, extremely high, with values that would seem able to allow the solution of the vast majority of shielding problems. In reality, those values must be interpreted as indicative of the shielding properties of the material in itself, rather than of the artefacts made with it. The situation indeed becomes far less optimistic when one moves on to consider real situations, in which one no longer deals with indefinitely extended plates, but rather with enclosures provided with apertures.

There are effects, such as dimensional resonances, that worsen the shielding effectiveness of an enclosure — even a hermetically sealed one — compared with that of an ideal shield. But by far the greatest degradation comes from the need to make apertures in the enclosures, such as, for example, the doors and windows in the rooms of dwellings. Schematising the problem, apertures indeed constitute passages through which the electromagnetic field can cross a metallic shield, thus causing a reduction of the shielding effectiveness, whose extent depends mainly on the dimensions of the aperture relative to the wavelength.

Each aperture can be characterised quantitatively by a figure of merit, commonly called the aperture loss, for which we shall use the symbol L_{dB} (resorting, as usual, to the logarithmic formulation in decibels); attention is drawn to the fact that a smaller value of the factor L_{dB} corresponds to a greater loss, and hence to a more marked worsening of the shielding. Under simplifying and precautionary assumptions, it is possible to show that the shielding effectiveness SE$^{(a)}$_dB inclusive of the effect of n apertures, each characterised by a loss L$^{(i)}$_dB, can be computed from the initial one SE_{dB} of the shield alone with the following relation:

$$\mathrm{SE}_{\mathrm{dB}}^{(a)} = -20\log_{10}\left(10^{-\frac{\mathrm{SE}_{\mathrm{dB}}}{20}} + \sum_{i=1}^{n} 10^{-\frac{L_{\mathrm{dB}}^{(i)}}{20}}\right) \tag{13}$$

Expression (13) is interesting because it shows how the overall shielding effectiveness is heavily conditioned by the loss mechanisms, i.e. by the apertures. Indeed, in many cases, it is the worst of the apertures (the one, that is, characterised by the lowest value of the parameter L_{dB}) that actually determines the final shielding effectiveness of a shield.

6.1 Assessment of the loss of an aperture

Let us first consider a rectangular aperture of dimensions W × S, with W ≥ S. The shielding loss it causes depends on the direction of polarisation of the electric field; since, in general, this direction is not known, one must precautionarily refer to the worst case, which occurs when the long side W is directed orthogonally to the electric field. Qualitatively, what happens in this case, at least for elongated apertures that are small compared with the wavelength, is that the surface currents present on the shield are interrupted by the aperture and cause the appearance of an electric dipole oscillating between its two nearby edges, which radiates (also) towards the other side of the shield. An aperture aligned parallel to the field, on the other hand, perturbs the current distribution on the shield less, and hence its shielding effectiveness, as illustrated in Figure 3.

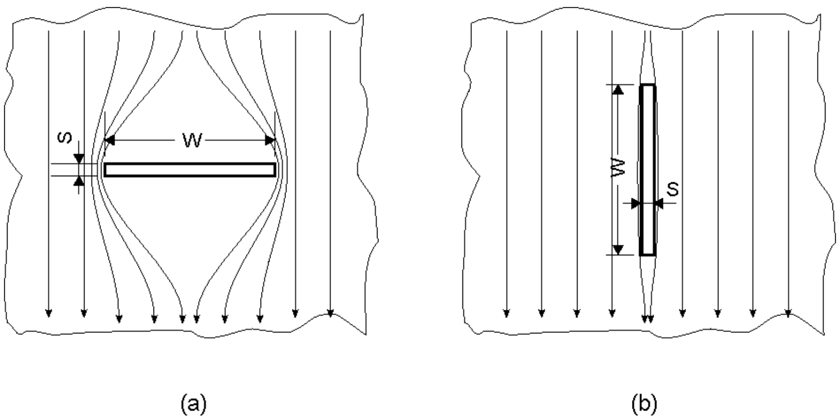

Figure 3. *Qualitative representation of the effect of an aperture on the current distribution on the surface of a flat shield.*

It is possible to build an analytical model that leads to estimating the loss of an aperture by establishing a formal analogy with a coplanar "parallel-plate" transmission line; one arrives at the following expression:

$$L_{\mathrm{dB}} = -12.5\mathrm{d}B + 10\log_{10}\left(\frac{\lambda^2}{WS}\right) + C \qquad (14)$$

where the corrective term C, generally of small magnitude, takes into account two secondary effects, called respectively the "waveguide-below-cutoff effect" and the "shadow effect". Put very briefly, the first effect takes into account the finite thickness of the shield in which the aperture is made, and hence the attenuation undergone by the field in traversing it, while the second refers specifically to closed enclosures (i.e. it does not exist in flat shields) and is due to the radiation pattern with which the aperture illuminates the inside of the enclosure.

As can be seen from equation (14), the quality of the shielding degrades more and more (i.e. the parameter L_{dB} decreases) as the frequency grows; there is however a lower limit to this phenomenon, because it can be shown that the loss L_{dB} of a given aperture does not fall below a minimum value expressed by:

$$L_{\mathrm{dB}} \geq 6 \log_{10} \left(\frac{W}{S} \right) + C \tag{15}$$

For example, an aperture of 10 cm × 1 mm at the frequency of 10 MHz entails a loss L_{dB} whose main term (i.e. excluding the corrective factor C) is worth about 57 dB. If it constitutes the only loss mechanism in a shield with an SE_{dB} of 75 dB, from equation (13) one finds that the overall shielding effectiveness is reduced to 56 dB, i.e. in practice it is determined almost totally by the aperture itself. It therefore degrades more and more as the frequency grows, down to a minimum value of 12 dB, as established by equation (15).

The considerations set out for a rectangular aperture also apply to a circular aperture of diameter D, provided that in (14) the product W·S is replaced by the area of the circle $\pi D^2/4$ and in (15) one sets W = S = D.

7. Conclusions of part one

The fundamental definitions and concepts pertaining to the problems of shielding an electromagnetic field have been introduced. A simplified theoretical model has been presented, capable of describing the behaviour of a flat metallic shield, predicting its properties, estimating its shielding effectiveness and assessing the effects of the apertures made in it.

The theoretical model must be considered as a guideline for tackling the initial steps needed to solve a problem of reducing exposure to an electromagnetic field through the use of shielding.

Part two: the reduction of the magnetic field of power lines

The need to reduce the levels of power-frequency (50/60 Hz) magnetic field generated by high-voltage power lines is strongly felt because, against values that in the vicinity of the most impactful lines can exceed ten or so microtesla, there are controversial reports of possible risks already at levels of a few tenths of a microtesla. Cases are therefore not rare in which one would like to have exposure containment techniques able to knock down the field present in a residential environment with an effectiveness above 10 and sometimes even 20 dB.

8. Possible approaches

As already noted, exposure containment techniques can be classified into three categories, which we summarise here with particular reference to power lines.

1. Techniques that act on the source, intrinsically reducing its emission for the same nominal characteristics (operating voltage and transported power): a. use of supports with compact geometry, with reduced spacing between the various phase conductors; b. use of three-phase cable lines with solid insulation, overhead or buried (in the buried case there is also a shielding effect of the ground, which however concerns the electric field only); c. adoption of split-phase wiring configurations including, to cite the simplest case, the use of a double circuit in place of a single circuit.
2. Measures that exploit the attenuation of the field with distance and therefore aim to move the conductors of the power line away from the sensitive sites: a. increase of the height of the supports (i.e. raising of the line); b. choice of an alternative route, moving the power line away from the sensitive site considered.
3. Recourse to shielding properly so called, i.e. to devices that knock down the field to which the victim is exposed, without acting directly on the emission of the source and without moving the victim away from it: a. traditional shielding: it requires plates of ferromagnetic material of considerable thickness and therefore gives rise to bulky, heavy, costly infrastructures which are often difficult to fit into residential environments; b. use of active or passive compensation circuits.

More advanced technologies also exist, into which we shall not be able to delve. We limit ourselves to mentioning gas-insulated enclosed power lines, in which advantage is drawn both from the compactness of the structure and from the existence of a metallic enclosure.

9. Assessment of the effectiveness of the intervention

The availability of a tool for the theoretical assessment of the expected field levels is a fundamental prerequisite for the analysis and application of an exposure reduction technique. Such a tool not only facilitates the identification of the situations requiring an intervention but, above all, makes it possible to assess in advance the degree of effectiveness of the various applicable solutions, allowing the most suitable one to be chosen.

The case of high-voltage power lines is, in this respect, among the most fortunate, because the dispersed magnetic field can be determined theoretically with good precision, starting from a set of technical information that is usually reasonably accessible.

In most cases, sufficiently accurate results can be obtained using a calculation algorithm based on a two-dimensional model of the electric line, in which the power line is assimilated to a bundle of indefinitely long straight conductors, parallel to one another and to the ground. This model is codified in a specific CEI standard [2] and can be implemented without particular difficulty in any programming language, or even simply with an ordinary electronic spreadsheet. The algorithm in question is also described in detail in the manual of the CAMPI program developed at CNR-IFAC [3], with which the assessments presented in the next section were carried out.

10. Analysis of some of the available methods

We now present a closer look at some of the methods cited above.

10.1 Use of compact supports

The magnetic field generated by a power line depends appreciably on the mutual distances between the various conductors constituting the line, so that the adoption of "compact" supports, which tend to reduce those distances as much as possible, entails a marked reduction of the field intensity at all points surrounding the power line, also and above all at a certain distance from it.

10.2 Undergrounding

The undergrounding of a section of line entails an almost total reduction of the electric field, thanks to the shielding action exerted by the ground; the latter, in fact, unlike air (which can be assimilated to an insulator), behaves as a good electric conductor.

What interests us most here, however, is the greater compactness (i.e. the smaller mutual spacing between the various conductors) of a buried power line compared with the overhead configuration, made possible by the use of insulating materials characterised by a dielectric strength better than that of air.

The compactness of the structure determines a rapid attenuation of the magnetic field intensity as the distance from the line increases. Consequently, while in the immediate vicinity of a buried line one must expect values of the same order of magnitude as those found under an overhead line of corresponding characteristics, as soon as one moves even a few metres away from the buried line the expected values decay very rapidly to levels that, for the overhead line, would require distances of many tens of metres.

This is clearly visible in Figure 4, which reports the lateral profiles at 1 metre from the ground of the magnetic flux density generated by a single-circuit 132 kV / 450 A power line, of the overhead type with standard lattice supports and of the buried trefoil type; in the first case the lowest conductor is at a height of 18 metres from the ground, in the second the centre of the trefoil is buried at a depth of about 1.5 metres.

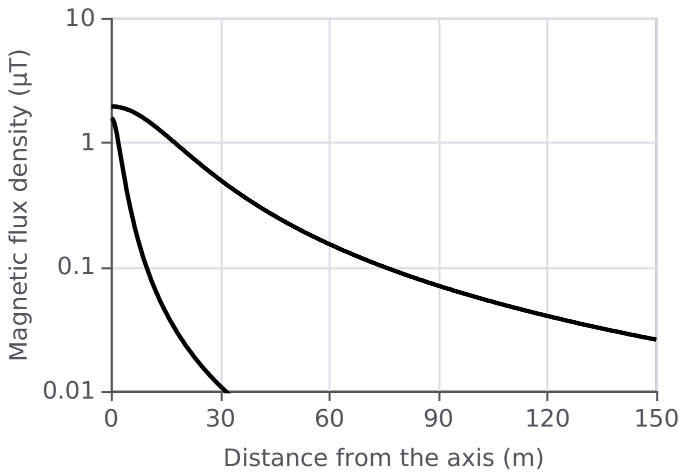

Figure 4. *Lateral profile of the magnetic flux density at 1 metre from the ground, generated by a single-circuit 132 kV / 450 A power line; upper curve: overhead line with standard lattice supports and lowest conductor at 18 metres from the ground; lower curve: buried trefoil line with the centre of the trefoil at a depth of about 1.5 metres.*

10.3 The "split-phase" technique

One of the most effective techniques to knock down the magnetic field generated by a power line is the one known by the term split-phase, which consists in dividing among two or more conductors the current transported by a single phase conductor, so as to have smaller currents on each conductor and, at the same time, to be able to choose the wiring configuration so as to obtain the maximum cancellation among the contributions of the conductors themselves to the total field.

A minimal form of this technique may consist in converting a single-circuit section to an optimised double circuit, for the same voltage and transported power.

Figure 5 illustrates the result of replacing a 380 kV / 1 MW single-circuit section (current 1500 A) with an optimised double-circuit one of equal voltage and power (the current thus drops to 750 A); as usual, the figure reports the lateral profile of the magnetic flux density at 1 metre from the ground. In both cases, reference is made to standard lattice supports and to a minimum height of the conductors of 25 metres from the ground.

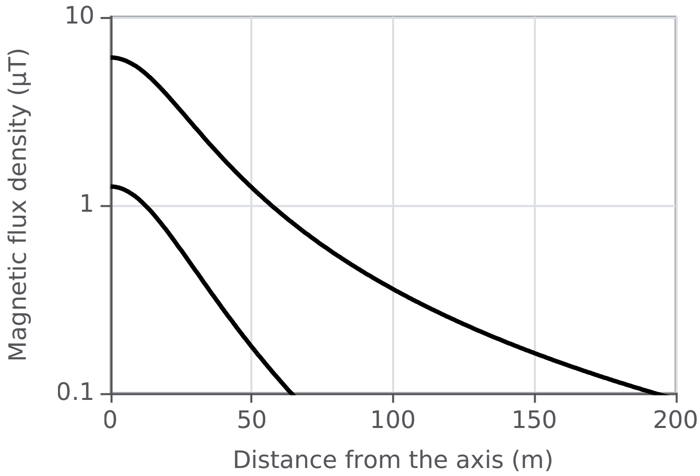

Figure 5. *Lateral profile of the magnetic flux density at 1 metre from the ground, generated by 380 kV / 1 MW lines with standard lattice supports and lowest conductor at 25 metres from the ground; upper curve: single-circuit line (current 1500 A); lower curve: optimised double-circuit line (current 750 A).*

10.4 Raising of the supports

Generally speaking, increasing the height of the supports means moving the conductors away from the sensitive sites and hence reducing the field evaluated at those points. A clarification is however needed. The method turns out to be fairly effective in knocking down the values found directly below a power line or in its immediate vicinity (a few tens of metres at most), while it is rather ineffective in reducing the values at a certain distance (beyond a hundred metres or so). This behaviour is well documented in Figure 6, which shows the lateral profile of the magnetic flux density at 1 metre from the ground, generated by a single-circuit 380 kV / 1500 A power line with standard lattice supports; in the figure, the situation in which the lowest conductor is at 15 metres from the ground is compared with the one in which the minimum height from the ground is 35 metres.

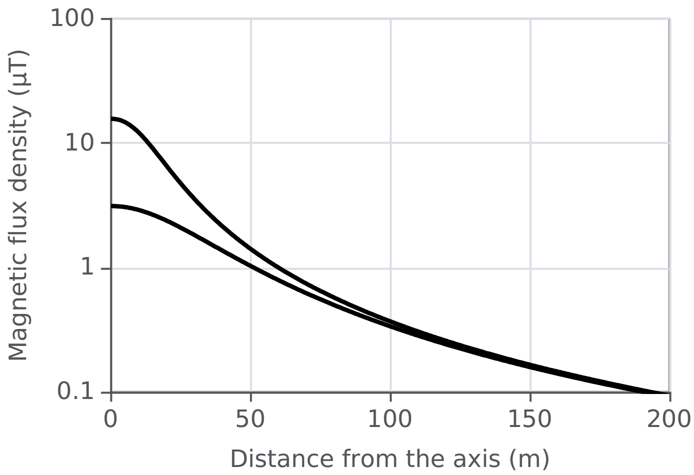

Figure 6. *Lateral profile of the magnetic flux density at 1 metre from the ground, generated by a single-circuit 380 kV / 1500 A power line with standard lattice supports; upper curve: lowest conductor at 15 metres from the ground; lower curve: lowest conductor at 35 metres from the ground.*

10.5 Route alternatives

The choice of an alternative route may in some cases represent a possibility to reduce the magnetic field present at a sensitive site, whenever the alternative makes it possible to increase the distance of that site from the power line that is the source of the field. As a rough indication, it may be useful to remember that the magnetic field at a large distance from a power line ("large" compared with the mutual distance between the conductors of the line) is, to a good approximation, inversely proportional to the square of the distance itself.

Regarding alternatives, the following considerations must be kept firmly in mind, in case the final objective is the reduction of the carcinogenic risk hypothetically associated with exposure to the magnetic field.

If we admit that the magnetic field may actually play a role in the development of some types of tumours then, according to many authoritative opinions, one must take into consideration the possibility that this effect has no threshold, and that there exists instead an increase in risk proportional to the level of exposure. According to this hypothesis, values however low could have health relevance, especially if associated with the exposure of a numerous population. In other words, the overall health impact would come to depend not only on the field level, but also on the size of the population sample exposed to that level. In this situation, the relocation of a line aimed at bringing the expected field value at an isolated site below a preset value (for example 0.4 µT) could entail an increase, rather than a decrease, of the overall health impact if, for example by bringing the line closer to a cluster of buildings, a (small) increase in the exposure of a large number of individuals is caused, even though the exposure itself remains everywhere below the preset limit value. Naturally, this consideration ceases to be relevant if one accepts the existence of a threshold below which the risk vanishes: in this regard, the June

2001 pronouncement of the IARC (International Agency for Research on Cancer) should be recalled, according to which "Children who are exposed to residential ELF magnetic fields less than 0.4 microTesla have no increased risk for leukaemia".

10.6 Shielding of the power-frequency magnetic field by means of compensation circuits[3]

A method of reducing the magnetic field generated by a power line which, to all intents and purposes, can be considered a form of shielding, albeit an unconventional one, is the technique based on the use of so-called compensation circuits.

The basic concept is simple: a conductor forming a closed circuit is positioned in the region where the field is to be reduced, and an alternating current at 50 Hz is made to flow in it, so that the magnetic field it generates cancels as much as possible the field generated by the power line to be shielded.

Unlike shielding realised by means of plates and enclosures, the great accuracy with which it is possible to determine the magnetic field generated by a set of conductors, combined with the low influence that buildings and other objects have on it, makes it possible to fully characterise a compensation circuit from the theoretical point of view, or to predetermine its performance with great precision at the design stage. For this purpose, dedicated software tools exist that make it possible to optimise the numerous parameters at play in order to minimise the field in the area occupied by the victim.

The technique comes in two conceptually distinct variants: the use of active compensation circuits — in which a dedicated generator takes care of maintaining the right current in the shielding circuit — or of passive circuits, where the current in the circuit is generated by electromagnetic induction precisely by the flux of the magnetic field one wishes to shield. In the latter case, advantage is drawn from Lenz's law which, as is well known, establishes that the magnetic field generated by the induced current tends to cancel the primary field that generated it.

Both variants have advantages and disadvantages. In the case of passive circuits, there is a limited margin of manoeuvre for the control of the current, since one can act only on the impedance of the circuit itself. With active circuits, it is instead possible to act on the supply generator as well. The latter therefore allow, at least in theory, better results to be obtained, at the cost however of a greater complexity and costliness of the system.

Solutions based on compensation circuits always present a certain impact, both economic and visual. Both can be limited by integrating the earth wires into the circuit, thus decreasing the number of new conductors to be inserted into the system. The visual impact (but not the

3. This section is a synthesis of a section of the chapter "La schermatura dei campi elettromagnetici", by D. Andreuccetti and C. Riminesi, in "La schermatura dei campi elettrici, magnetici ed elettromagnetici: principi generali, aspetti teorici e applicazioni pratiche", Franco Angeli Editore, Milan 2006, edited by Paolo Bevitori.

economic one) can also be limited by burying part of the compensation circuit. In any case, these expedients obviously penalise the optimisation possibilities linked to the positioning of the conductors.

The main difficulty encountered with compensation circuits lies in the fact that, while the field generated by the line has elliptical polarisation, the one generated by the compensation circuit has instead linear polarisation, and is therefore able to cancel the primary field only in part and only locally. For this reason, it is difficult to reach shielding effectiveness values above 20 dB with a compensation circuit and, in any case, only in very limited areas. More easily, or over more extended areas, values up to 10 dB can be obtained.

11. Conclusions of part two

Several technical measures exist that can reduce the level of the magnetic field generated by a power line. The raising of the supports, the identification of alternative routes and undergrounding represent some of the available options, although they entail numerous problems of various kinds; interesting and in some respects less problematic possibilities consist in the adoption of supports with compact geometry and in the transformation of single-circuit sections into double-circuit ones; good results in particular cases can be obtained with the adoption of active or passive compensation circuits.

For carrying out the control activity, for identifying the sites requiring interventions and above all for the preventive verification of the effectiveness of the various available solutions, the availability of a tool for the theoretical assessment of the magnetic field generated by a power line is of great help. A specific CEI standard, 211-4 [2], describes an easily implemented algorithm capable of providing results adequate for use in applications of this type.

In any case, once the criteria for deciding in which cases to intervene have been defined, and the sites where an intervention is required have thus been highlighted, the cooperation of the infrastructure operator is needed to establish which technical measure is best suited to each contingent situation. Those charged with the control may subsequently take on further assessments to ascertain the effectiveness of the intervention and the extent of the benefit achieved.

References

[1] J.D. Kraus: "Electromagnetics", McGraw-Hill International Student Edition, Singapore 1984.

[2] CEI (Italian Electrotechnical Committee): "Guida ai metodi di calcolo dei campi elettrici e magnetici generati da linee elettriche" ("Guide to the calculation methods of electric and magnetic fields generated by power lines"), Standard CEI 211-4, Milan, 1996.

[3] D. Andreuccetti: "Manuale del programma CAMPI per il calcolo del campo elettrico e dell'induzione magnetica generati da linee elettriche versione 4.1" ("Manual of the CAMPI program for the calculation of the electric field and magnetic flux density generated by power lines, version 4.1"), CNR - "Nello Carrara" Institute of Applied Physics, Florence, May 2002, http://www.ifac.cnr.it/pcemni/manuale.pdf.

[4] Various authors: "La schermatura dei campi elettrici, magnetici ed elettromagnetici: principi generali, aspetti teorici e applicazioni pratiche" ("The shielding of electric, magnetic and electromagnetic fields: general principles, theoretical aspects and practical applications"), Franco Angeli Editore, Milan 2006, edited by Paolo Bevitori.