Practical Experience with Mitigation of Magnetic Fields from Electric Traction
Wouters, P.A.A.F.; van der Laan, P.C.T.

Published in:
Proc. XIVth International Symposium on High Voltage Engineering, Beijing, China, August 2005

Published: 01/01/2005

Document Version
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Citation for published version (APA):

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Download date: 11. Dec. 2018
Abstract: In densely populated areas electromagnetic fields from power equipment may have to be reduced for basically two reasons: (i) to avoid interference with sensitive equipment, and (ii) to lower human exposure to these fields. This paper compares passive field mitigation strategies based on both ferromagnetic and non-ferromagnetic shielding. The strategies are illustrated by means of a number of case studies. In contrast to what is often naively believed, it is concluded that shielding by ferromagnetic material must be discouraged in many practical situations.

INTRODUCTION

In urban areas a public transport system is vital to prevent traffic congestion. Transport based on electric traction is preferred from an environmental point of view: relatively low fuel consumption, less acoustic noise, and hardly any exhaust gases released directly in the urban areas. On the other hand, electric traction inevitably leads to exposure of people to low-frequency magnetic fields. Lately, much attention is paid to possible health effects of magnetic fields. With many others we feel that adverse health effects, if any, are by far outweighed by the benefits from much lower direct atmospheric pollution. This does not mean that the magnetic fields are of no concern. Highly sensitive equipment is usually present in e.g. offices, hospitals, and laboratories. This brings B-field mitigation again within the working area of electrical engineers, as it should, instead of being part of a highly speculative health issue.

Reasons to reduce B-fields, in particular those at the mains frequency (50 or 60 Hz), are:

1. B-fields near computer monitors, as being one of the most sensitive devices for low-frequency B-fields, should be < \(1 \mu T\) to avoid annoying distortion of picture or text on a monitor screen [1]. For DC much higher levels can be accepted.

2. B-fields in the human body should be < \(100 \mu T\). This limit is given in the ICNIRP guideline [2,3] as a limit for the general population, 24 hours a day.

In this paper shielding strategies and their effectiveness are discussed. Ferromagnetic and non-ferromagnetic shielding against low-frequency magnetic fields will be demonstrated by simulation and experiment. A number of case studies from recent projects will be discussed in view of the shielding mechanisms involved.

SHIELDING METHODS

Several methods to reduce B-field exist. We may reduce the field already at the source, near the victim or somewhere in between. What the most cost-effective method is depends on the situation. The source can be leads which carry high 50 Hz currents. It is important to keep the leads - two or three-phase leads or bus bars - close together. This approach reduces the B-fields provided the net or zero-sequence current is zero. Whenever this is not true the return path for the zero sequence current has to be found so that also the size of that loop can be reduced. Any shielding is bound to fail in a situation where the return conductor is far away, since -according to Amperes law- the magnetic field component in the direction of a closed integration path must be equal to the enclosed current.

If the distance between source and victim cannot be increased, some form of a shield can be introduced. Shielding with magnetic materials (\(\mu >> 1\)) relies on “magnetostatic shielding” (the term “magnetic shunting” is also used [4]), metals as aluminium or copper provide “eddy current shielding” only. These two shielding mechanisms, the only mechanisms available for passive shielding of B-fields, are quite different in nature.

To illustrate that, we consider an infinitely long strip of shielding material (Fig. 1) with thickness \(d\) and width \(w\). A homogeneous B-field is either directed perpendicular or parallel to the strip. We consider six situations; in the first two the B-field is static whereas in the other four the B-field has a 50 Hz sinusoidal time variation. In Fig. 1 the field direction and strength are indicated. The inserts show the field enhancement just above the shielding with respect to the impressed field.

1. The ferromagnetic strip perpendicular to the B-field offers the B-lines a slight reduction of the magnetic “reluctance”; the short length \(d\) is shortened to \(d/\mu\), which does not modify the field much since it is mainly determined by the large path in air. At the edge of the strip the field is modified but only over distances comparable to \(d\).

2. With the strip parallel to the field, the B-lines now follow a much longer path through the strip and the B-field is modified over distances comparable to \(w\). Close to the strip the B-field is considerably reduced.
3. The non-ferromagnetic strip carries eddy currents induced by the perpendicular 50 Hz B-field. It can be shown [5] that the eddy currents modify the field strongly when the condition \( w \cdot d >> \delta^2 \) is fulfilled; \( \delta \) is here the skin depth, which is equal to \( \sqrt{2\rho / \mu_0 \omega} \) with \( \rho \) the specific resistivity and \( \omega \) the frequency of the B-field. The effect of the eddy currents is to push the field lines as much as possible out of the metal. Therefore, near the metal the B-field is strongly reduced.

4. No B-field lines intersect with the strip and no eddy currents flow for a parallel field. The field is not modified. The effect of eddy currents is limited due to the low thickness of the strip.

5. The ferromagnetic strip perpendicular to the 50 Hz B-field is complicated. Both “magnetostatic shielding” and “eddy current shielding” are active in this case. We expect a mixture of the situations 1 and 3. The ferromagnetic material has a higher resistivity \( \rho \) than copper; however, the skin depth \( \delta \) is nevertheless smaller because the factor \( \mu_r \) is in the denominator of the expression for \( \delta \). With this orientation of the strip eddy currents are mainly responsible for the shielding. Note, that both shielding mechanisms are not synergetic, since the field reduction in the centre is higher for situation 3 than for situation 5.

6. The ferromagnetic strip in a parallel 50 Hz field may look like a mixture of the situations 2 and 4. However, for this orientation of the strip the magnetostatic shielding is dominant, since practically no eddy currents are induced.

![Fig. 1 Simulation of field mitigation of an incoming homogeneous field perpendicular to the strip (left figures) and parallel to the strip (right figures). The arrows indicate the field direction and the brightness the field strength (lighter colours correspond to higher field strengths). The inserts show the B-field value calculated over the full width of the shielding structure just above shielding plane.](image)
MEASURED SHIELDING

The shielding effectiveness has been measured for an 8 mm thick aluminium strip and for a 0.6 mm ferromagnetic material with $\mu > 1000$. A 10 A current loop is formed by a forward and a return conductor 10 cm apart, 25 cm below the plane where the shielding strip with a width of 60 cm can be positioned. The horizontal ($B_x$) and vertical ($B_y$) component were measured at two heights, namely at 16 cm and 28 cm above the shielding plane. In Fig. 2 the field strength for ferromagnetic (triangles) and non-ferromagnetic strip (squares) are shown together with the unshielded values (diamonds). The shielding by virtue of eddy current is clearly more pronounced, especially for the vertical field component. From this observation it is concluded that for many practical situations, where shielding structures are essentially open structures, non-ferromagnetic materials like copper or aluminium must be preferred. Besides the shielding properties, aspects as machining, installing and price favour usually the use of these metals. In closed structures like tubes the performance of ferromagnetic materials is much better because the magnetic circuit is closed [5].

CASE STUDIES

Various considerations for shielding in practice are discussed in the following examples. The first case study concerns the situation of 25 kV high-speed trains,
powered with 50 Hz AC. The second example is related to shielding of the power connection to the rectifier for a tram, placed in the basement of an apartment building. The third example deals with situations where a tram passes underneath a building.

Field Reduction in a Railway Carriage

Railway traction lines result in relatively high fields inside a carriage, if these fields are not screened properly. In order to simulate a railway carriage, a very simplified model is chosen. The carriage is considered as consisting of two “trays” making up a square of, say, 3 m by 3 m. The windows are modelled as an interruption left and right with a height of 60 cm. As material, 4 mm Al is applied. The traction current is simulated by one conductor 1 m above (catenary: 500 A) and two below (rails: each 250 A) the carriage. This current is typical for a fully accelerating high-speed train.

Fig. 3 Magnetic field distribution inside a railway carriage (4 mm Al, resistivity 2.69 $\times$ $10^{-8}$ $\Omega$m) from +500 A and –500 A, 50 Hz currents at top and bottom.

For the two-dimensional magnetic field calculation an assumption has to be made concerning the current carried by the carriage. Obviously, the total current of the carriage will be zero. However, the interconnections between top and bottom, especially at the ends determine whether each of both “trays” will carry zero current (no connection) or that only the net current is zero meaning that both trays carry equal but opposite currents (good connection). The field strength inside the railway carriage is shown in Fig. 3. The curves give the values in the centre (along a horizontal line between the windows, see insert Fig. 3) of the carriage. Curve (a) represents the unshielded situation (no carriage). Curve (b) gives the situation that the upper and lower parts are independent. Here, no effective shielding occurs. However, if at the ends of the carriage the upper and lower parts are interconnected well, a passive compensation loop is present, reducing the B-field to below 1 $\mu$T near the windows.

As at high speed often one pantograph is used, the power cabling to the engine at the other end of the train has to pass beneath the carriage [6]. Also here shielding can only be effective if the return current is close to the forward current. If the return current follows a perfectly coaxial path, e.g. over a tube, no fields will be present outside this tube. The tube can be made of aluminium. A ferromagnetic tube must be preferred if it encloses a parallel forward and return conductor. For proper shielding such a tube should be fully closed [7,8].

 Shielding Three-Phase Current for Tram

In densely populated residential areas, transformers (and rectifiers) for power supply to trams are often placed inside the basement of an apartment building. In a particular case, accelerating trams (over 1 kA) disturbed a television set situated just 50 cm above the ceiling of the basement. The magnetic field strength reached values as high as 100 $\mu$T. A reduction factor of 10-20 was therefore required to ensure proper picture representation. In the configuration of one transformer feeding a rectifier system, the current paths are well defined and the zero sequence current remains small. Therefore, it was decided to apply eddy-current shielding by installing an aluminium shield between the ceiling and the three phase conductors (30 cm spacing) about 50 cm below.

In Fig. 4 various shielding configurations are simulated. The magnetic field strength is calculated over a distance of 3 m at a height of 1 m above the conductors (along the dashed line shown in the insert of Fig. 4). The maximum field $B_m$ represents the field magnitude occurring on these positions. The use of only metal plates, 2 m wide, thickness of 1 mm, 3 mm and 10 mm resulted in a field reduction of a factor 3.4 (curve b), 5.9 (curve c) and 6.4 (curve d) respectively with respect to
the unshielded situation (curve a). Apparently, unrealistic material thickness should be applied to obtain the desired field reduction. As an alternative, a combination of two shields was applied: a plate as above together with a tray 20 cm above the conductors (as shown in Fig. 4) both Al, and 3 mm thick. With this configuration a reduction of a factor 15 was obtained (curve e), which proved to be sufficient.

**Shielding B-Fields from Trams below Buildings**

New tramlines are sometimes projected underneath buildings, or new buildings are planned over existing tramlines. Tramlines usually are powered with DC with a superimposed alternating current due to the rectifier ripple and to the traction harmonics. Also high-frequency EM-disturbances from the pantograph should be taken into account. In the first example, a tramline is situated beneath a passageway between the parts of a hospital. The DC field distribution is given in Fig. 5.

**CONCLUDING REMARKS**

Which type of shielding method should be applied depends on the specific situation. The first aspect is to control the current loop. Shielding a zero sequence current component is virtually impossible. It was shown, that in many cases, non-ferromagnetic materials like aluminium can accomplish proper shielding. In addition, for open structures ferromagnetic materials can cause strong field enhancement at the edges. Evidently, for closed tubes ferromagnetic material outperforms non-ferromagnetic material. However, eddy current shielding may already be sufficient and materials like Al or Cu are usually easier to machine and to install.

**ACKNOWLEDGEMENT**

The authors like to express their gratitude to Rob Verhoeven of SMIT Transformers, Nijmegen, The Netherlands for providing highly permeable ferromagnetic material.

**REFERENCES**


