INTRODUCTION OF MASS TRANSPORT SYSTEMS: LF EMC ASPECTS

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Abstract

The last few years in The Netherlands there has been a growing interest in light rail systems in order to reduce congestion in major cities. In the past d.c. systems rarely led to EMC issues, as the number of systems susceptible to low frequency E.M. fields was very limited. Also power demand was limited. In order to provide high quality fast transport, power demand is increasing. Also at the moment the number of systems which can be influenced by d.c. magnetic fields such as electron microscopes, NMR spectrometers and MRI scanners is growing, at the same time the immunity levels of this type of equipment are decreasing. This is hampering the introduction of light rail systems especially in the neighbourhood of hospitals and university complexes, where quite often the need for a good transport system is high.

In order to assess possible problems as early as possible, simulation software has been developed, taking in to account the effects of stray currents. Mitigation methods, such as alternative designs of the power supply system or modifications of rolling stock have, been studied. Also mitigating measures for the affected equipment have been studied, although this usually is not the preferred method. Major goal is to limit the mitigations along the line to the absolute minimum possible. For example, only the use of mitigating measures, for specific locations.

Example of mitigating alternative designs of the power supply system are sectioning of the catenary system, the use of capacitors and/or batteries in the trams or a trolley system. Concerning mitigating measures at the equipment side, one can think of different shielding methods, such as Helmholtz cages. Calculations for each situation (location along the line) should give an answer as to whether the reduction of the magnetic field emission (related to the emission of a “standard” catenary system) of a certain mentioned mitigating system will be sufficient enough. Another concerning issue is the level of (or the ripple on) the earth magnetic field. This phenomena should be taken into account as well.

Using the advanced simulation tools it is possible to detect potential problems in an early planning state, thus enabling all parties involved in projects to develop a solution (or solutions) which is/are feasible both from an economical as well as from a technical point of view.

1. Introduction

Magnetic fields, either d.c. or 50 Hz, caused by the introduction of mass transport systems in densely populated areas may need mitigation for either human beings, or disturbance of equipment. Shielding of LF magnetic fields in a practical situation is often more difficult than of HF phenomena. Shielding can be either active or passive, for the latter we can distinguish between using ferromagnetic and non-ferromagnetic material. Mitigating measures can be taken either at the source or at the victim side.

2. Physics

Normally for mass transport systems, LF magnetic field disturbances have two sources:

- Currents related to energy supply of the d.c. substations, causing 50 Hz fields;
- Currents related to traction power supply of the vehicles, causing d.c. fields with superimposed (traction) harmonics.

The magnetic induction of a linear conductor in air is given by:

$$B(r) = \frac{\mu_0 I}{2\pi r} \qquad (1)$$

This is independent of screening, only in case the screen carries a part of the return current damping will occur. In case the return conductor is close at a distance of *a*, the magnetic induction is given by:

$$B(r) = \frac{\mu_0 I}{2\pi r} \cdot \frac{a}{r} \qquad with\, r \gg a \qquad (2)$$

We see that in the first case the field strength which drops with $1/r$, whereas in the second case the field strength drops with $1/r^2$. In the second case screening can be applied successfully.

We can distinguish between two mechanisms of screening [1]:

- Magnetostatic, in case $\mu_r \gg 1$, ferromagnetic materials;
- Eddy currents [1], in case $\mu_r = 1$, materials like copper and aluminum.

For d.c. magnetic fields only the first mechanism can be used. It is only effective if net current passes through the system and the material does not saturate. Unfortunately for d.c. traction systems, always part of the return current will flow through “Mother Earth” as stray current. Therefore for d.c. traction systems screening at the source is likely to fail. On the other hand screening can be applied successfully for 50 Hz currents in substations, in case of absence of a zero sequence current.

3. Measures at source

For d.c. traction system only a few realistic scenarios exist to reduce d.c. magnetic fields:

- The use of a higher supply voltage, thereby reducing currents;
- The use of energy stored in the vehicle at sensitive locations;
- To reduce the distance between positive conductor and return circuit;

An example of the latter can be found in Fig. 1. Here the magnetic field for a tram system with a traction current of 2 kA in both lines is given.

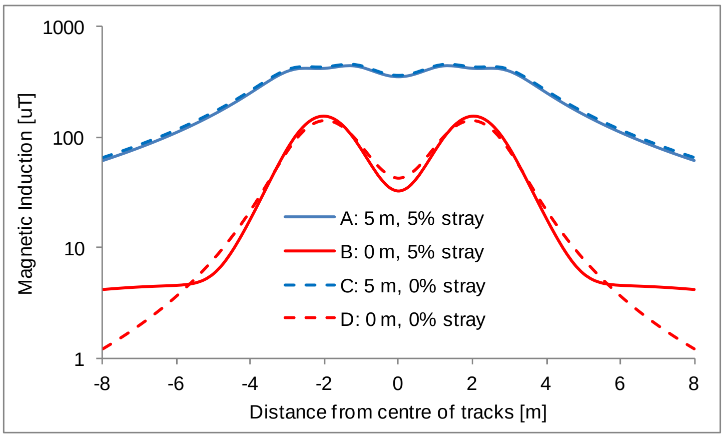

Figure 1 Magnetic field at a height of 1 m for dual line tram system

Four configurations are given. For curves A & C the catenary is at a height of 5 m. For curves B & D the positive conductor is at the same height as the running rails. For curves A & B (continuous lines) a realistic stray current of 5 % has been assumed, for curves C & D (dashed lines) a stray current of 0 % has been used. One can clearly see the effect of the reduction of distance, but simultaneously one also sees the effect of stray currents, curve D drops faster than B at distances larger than 6 m.

4. Measures for victims

Normally, as victims only (electro) technical systems are considered. However, as mass transport systems are normally used in densely populated areas, immunity of human beings should be considered as well. Although there is much discussion on the subject [2], usually the limits as given by ICNIRP are considered to be state of the art, see Table 1. As it can be seen from Table 1, much higher values are specified than acceptable for instance for CRT-monitors, where low-frequency B-fields should be less than typically 1 - 5 μT to avoid distortion [3].

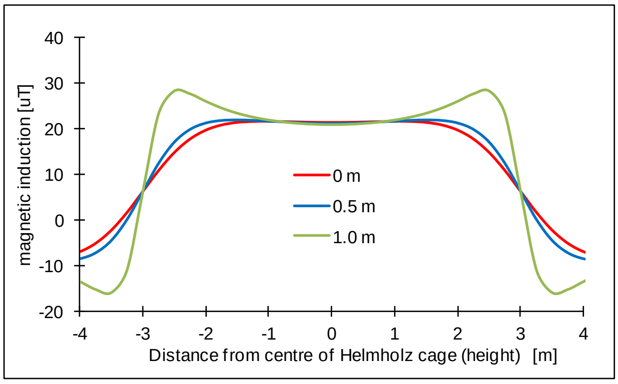

Figure 2 Magnetic field in Helmholtz cage, vertical planes

Table 1 Limit values as given by ICNIRP

	d.c.	50 Hz
General public	200 mT	100 μT
Occupational exposure	40 mT	500 μT

Quite often Helmholtz cages are seen as a proper solution which can be implemented for any victim, however this technique also has its limits. As example, in Figure 2 the magnetic field is given for a Helmholtz cage where the coils are 3 m apart, and 6 m in diameter. The magnetic field for vertical planes at different distances from the centre is given as function of the height. We can see that the field is constant over a volume of approximately 1 m x 1 m x 1 m. Also we observe that within this volume the field strength is not perfectly homogeneous, differences of approximately 5 % occur. This may seem small, but it limits the application of a Helmholtz cage in some cases. As the magnetic field of a tram can be 10 μT at a distance of 20 m, compensation in the cage might differ by 500 nT, where as some dual beam electron microscopes require homogeneity of less than 50 nT over a large volume.

For small objects magnetostatic shielding can be used, however for larger volume this is not practical. This can be illustrated by estimating the damping factor *A* of a cube with an edge of *W* and a material thickness of *d* with permeability μ_r. Using Hopkinson's law (magnetic reluctance [4]) we find:

$$A = \frac{W + 4d \cdot \mu_r}{W} \tag{3}$$

For *W* = 0.5 m, *d* = 5 mm, μ_r=1000 we find *A* = 41, which is a value which can be used for realistic purposes. It is obvious that for larger volumes material thickness has to increase to non-realistic values, or permeability has to be increased. The latter can be done by using for instance Mu-metal, which can have a permeability of 10^5. However these types of material saturate easily, are costly, and difficult to machine. Therefore practical use for large volumes is limited. For instance in case we use Mu-metal, with μ_r=5 x 10^4, for a cube with an edge of 5 m, and we need *A* = 400 we need a thickness of for the screen of 10 mm. This would lead to a weight of more than 10^4 kg, clearly a heavy and expensive solution.

5. Case studies

5.1 Metro Lisboa

The extension of Red Line from Alameda to Saldanha and S.Sebastião passes under the buildings of the Technical University, where system vulnerable to d.c. magnetic fields such as electron microscopes are present [5]. It was suggested to create a Faraday cage using a 30 mm thick iron tunnel lining. Using Oersted BEM software (IES) two situations were studied, a closed cylinder and a 250° cylinder with an opening at the bottom, see Fig. 3. The effect is low for the closed structure for realistic values of the permeability The open structure in some cases leads to locally stronger fields compared to no shielding. It should be noted that in case zero sequence current is present (stray currents) these fields are not attenuated at all by the lining, therefore other solutions for instance like Helmholtz cages around the sensitive equipment might be more economical. However here dual beam electron were present which require a “clean environment” over such a large area that Helmholtz cages could not provide a solution, so the equipment had to be moved to another location.

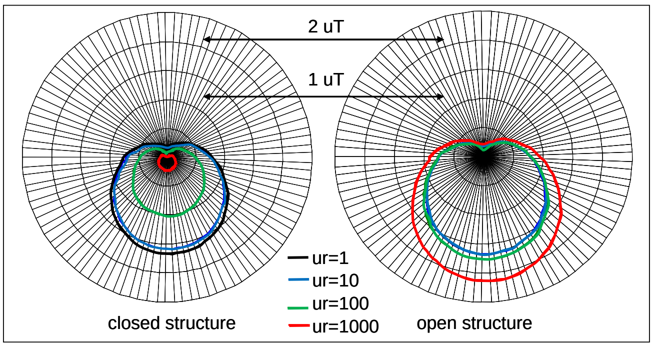

Figure 3 Magnetic flux on 18 m radius, as function of permeability.

5.2 Substation in basement

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 in Amsterdam, accelerating trams (over 1 kA) disturbed a television set situated just 50 cm above the ceiling of the basement. The B field reached values as high as 100 µT. 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.

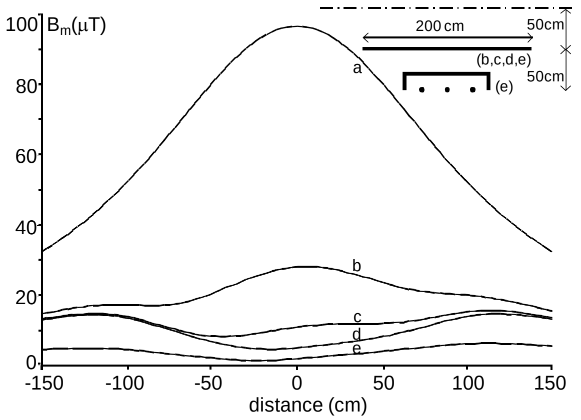

Figure 4 Field strength 1 m above a 1 kA three-phase current

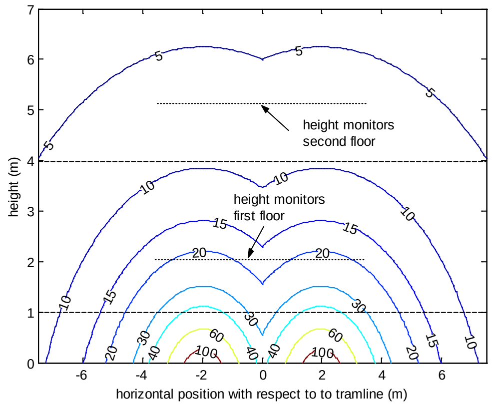

Figure 5 Iso-magnetic field lines [µT] for a tram passing under passageway

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.

5.3 Shielding B-Fields from Trams below Buildings

New tramlines are sometimes projected underneath buildings, like in this case a tramline was considered beneath a passageway between two parts of a hospital. Although a tramline is normally a d.c. system, 300 Hz or 600 Hz a.c. is present due to 6 or 12 pulse rectifiers, as well as traction harmonics. Sliding contact are responsible for high frequency emissions. European standards give limits for the EM-fields generated by a railway system [6], but only for a distance of 10 m. In an urban situation victims can be present closer than 10 m. The d.c. field distribution is given in Fig. 5. Note that distance is from the centre of the two tracks, field strength is for either a tram on the left or the right track, whatever resulted in the largest field. The levels at the first floor are just acceptable for a d.c. field according to [3]. The a.c. component could reach levels such that distortion of CRT images can occur. Therefore, Aluminium plating was used directly underneath the passage over the full width. This also prevented high-frequency coupling to a data communication link, which was present just above the ceiling of the passageway.

5.4 Adapted Traction Power Supply System

For a new tramline in Utrecht it has been decided to mitigate the LF magnetic fields at the source. As the tramline connects the city centre with the university campus, where a large number of systems susceptible to LF magnetic fields such as electron microscopes, NMR spectrometers and MRI. scanners. Initially also a system where energy is stored in the vehicle (super caps, batteries), where vehicles would circulate without catenary in areas where susceptible systems where present was contemplated. However the requirement that all rolling stock should be able to circulate, prevented this. It was decided to use the mechanism illustrated in Fig. 1, curves B & D. The main positive conductor is placed between the running rails. An overview can be found in Fig. 6. The section length can be varied depending on the magnetic field strength which is allowed, a typical value is 20 m. The field reduction which can be reached (due to train in section effect) is in the range 5-10 times. An overview of the magnetic field, train in section, single line, 1 kA can be found in Fig. 7.

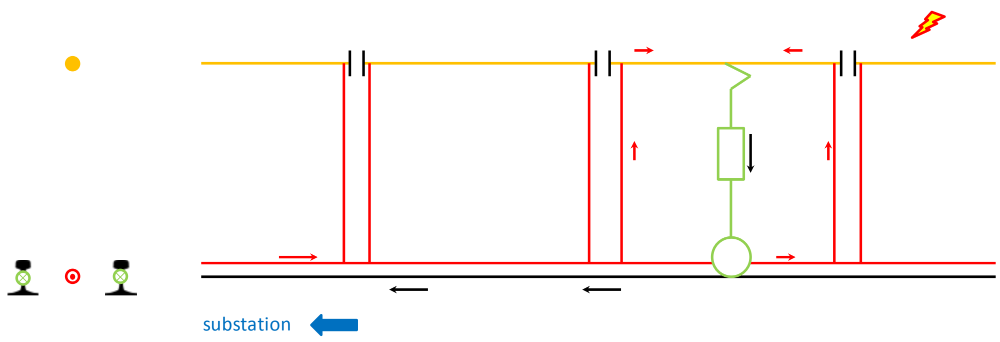

Figure 6 Overview of sectioning system

Main advantages of the system are the adaptability as section length can be varied, and that standard rolling stock can be used. A disadvantage is the large number of section insulators and thus increased construction and maintenance costs. Also due to sparking at the section insulators HF-emission will increase, and still the requirements of [6] have to be met. Also stray currents should be eliminated, as this would lead to a net current which only decays with 1/r. This means that rail insulation has to be high both after construction, as well as during the life time of the system.

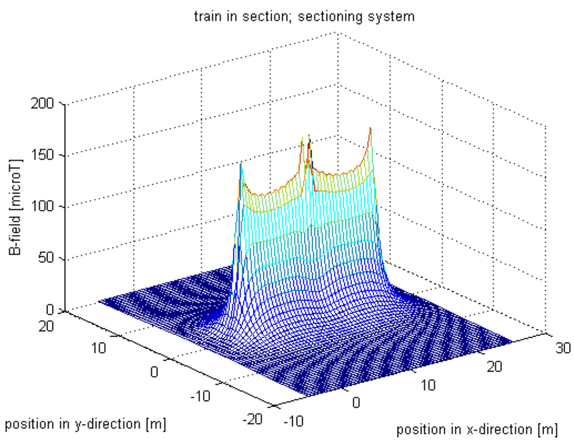

Figure 7 H-field (3D) of sectioning system, in section

6. Conclusions

In overview we can conclude that although nowadays much EMC research effort is directed to the HF range, there are still a lot of problems to solve at the LF end of the spectrum. Shielding at the source remains problematical in case a net current exists. Magnetostatic shielding can be applied, but is limited to relatively small volumes. Contrary to widespread belief, ferromagnetic materials are not to be preferred in all cases to screen a source. Therefore in practical cases the solution will be a combination of methods presented here, taking measures both at the source as well as at the victim. In case of extreme requirements, increasing distance (usually relocating the victim) is the only possible solution.

7. References

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