Low frequency Shielding Improvement by Multilayer Design

O. Losito[1], V. Dimiccoli[1], D. Barletta[1]
[1] ITEL Telecomunicazioni S.r.l.,
Ruvo di Puglia (BA) – Italy
e-mail: o.losito@itelte.it

Abstract— **It is well known that the common strategy to shield low-frequency magnetic field is to surrounding the volume of interest with ferromagnetic metal barriers. However it is as much known that a good ferromagnetic material is more expensive especially with high permeability ferromagnetic material and also is very heavy. In this paper, we have investigated a simple way to design a multilayer shield obtained with conducting shield and with magnetic shield, in order to valuate the attenuation of the magnetic field generated by a single-wire transmission line at industrial frequency rate. Using the Biot-Savart law, for the case of current conductors in air, we have analyzed our theoretical multilayer shield model, and compared it with experimental shielding effectiveness measurements made on a prototype of the screen. Experimental data shown a quite agreement with the theoretical model, highlighting as useful is this light weight multilayer screen, in the magnetic field shielding for industrial frequency rate.**

Keyword: magnetic shielding, multylayer shielding material, shielding effectiveness (SE).

I. Introduction

In the last years is growing the interest towards magnetic fields with extremely low frequency (ELF), produced by electric power systems, especially for medical diagnostic applications as MRI [1] and for the health effects upon human beings.

It is known as the most useful way to shield by the effects of these magnetic fields with extremely low frequency (ELF), is based on Schelkunoff's work [2] in which shielding theory has been developed to analytically predict the shielding effectiveness of various kinds of shields characterized by materials with magnetic linear property.

Generally we can divide the contributions of the total shielding effectiveness in three components: the reflection of the incident field at the first interface (rejection losses), attenuation of the transmitted field inside the shield (absorption losses), and multiple reflections.

Nevertheless the magnetic shielding process is characterized by several aspects: topology, material of the shield and type, location and orientation of the field source. However all kinds of used shields can be classified in two different magnetic shielding types: “passive” and “active” shields [3].

The active shield is characterized by the injection of currents into adequately designed active coils, in order to generate an opposite magnetic field that is superimposed to the excitation one. While passive shields represent the simplest and the cheapest way of shielding in common applications, characterized only by the use of metallic materials.

Also for a passive shields it is possible to use two different shield topologies: “closed” and “open.” Closed shields, which separe completely the source and the shielded regions, while open shields, do not [3].

The common strategy to shield static and low-frequency magnetic shield is obtained surrounding the volume of interest with ferromagnetic metal barriers.

This strategy is more expensive (especially with high permeability materials) due to the very heavy screen structure used.

An alternative to this strategy is to design and use as shown in our paper a multilayer shield with conducting shield and magnetic shield opportunely arranged, in order to assess the mitigation of the magnetic field generated for example by a single-wire transmission line at industrial frequency rate.

Our purpose was in fact to investigate only the case of open shield with a magnetic field source at industrial frequency rate (50 Hz).

The choice to use both conducting shield and magnetic shield were made mainly to reduce the overall material cost and its weight.

The good agreement between the theoretical model shown in the paper and its experimental data made on a simple prototype of three-layer screen (aluminum, air, steel SAE) allows to use this model to improve the shielding efficiency of the magnetic screen for industrial frequency rate without increasing the amount of metal employed.

II. Magnetic Shielding Mechanism

At low frequencies the magnetic field is due either to the electric current flowing in the generic conductors, or to the magnetization of surrounding ferromagnetic materials [4].

These ferromagnetic materials are characterized by high permeability values and are able to shield magnetic field thanks to the effect obtained by a mechanism called "flux shunting," in which the magnetic flux lines are deviated to enter the shield and so they don't reach the desiderata shielded region.

The nonferromagnetic or conductor metallic materials instead, present high electric conductivity values and a relative magnetic permeability near to unit. Their shielding effect is due to the "eddy current effect".

In fact eddy currents are induced in the metallic conductor, according to Faraday's law only for time-varying excitations currents, and their reaction field partially deletes the magnetic field of the source, near the shield.

The classical strategy to reduce quasi-static magnetic fields in a desiderata region consists to insert a shield of appropriate material, able to change the spatial distribution of the magnetic field emitted by the source, diverting the lines of the magnetic induction away from the shielded region.

The first step to develop our theoretical model of multilayer screen, is to verify the magnetic flux density generated by the current flowing in a single wire, in absence of any screen using the Biot-Savart law [5], for infinite straight wire with a *I* current:

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

where *r* is the distance between the source and the point in which calculate the magnetic flux density.

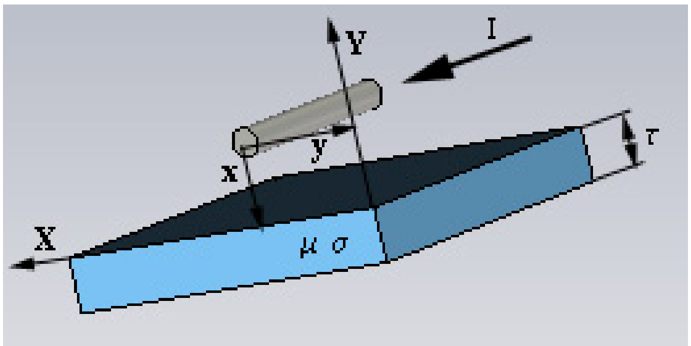

Figure 1. Layout of an ideal infinite plane to shield from a magnetic field generated by single wire of to develop the theoretical model.

For an ideal infinite plane shield as shown in Fig. 1 we can apply the theoretical expressions in [5]–[8] to calculate the field in (*xp,yp*) point excited by *I* current calculate as:

$$B_X(r) = \int_0^{+\infty} \frac{4W\mu_0 I}{\phi 2\pi} e^{-k(y_p - t - y)} \cos k(x_p - x) dk \tag{2}$$

$$B_Y(r) = \int_0^{+\infty} \frac{4W\mu_0 I}{\phi 2\pi} e^{-k(y_p - t - y)} \sin k(x_p - x) dk \tag{3}$$

$$B_T(r) = \sqrt{B_X^2 + B_Y^2} \tag{4}$$

where :

$$W = \frac{\mu_r k}{\sqrt{k^2 + j\omega\mu_0\mu_r\sigma}} \tag{5}$$

$$\phi = (1+W)^2 e^{\gamma t} - (1-W)^2 e^{-\gamma t} \tag{6}$$

$$\gamma = \sqrt{j\omega\mu_0\mu_r\sigma} \tag{7}$$

and *k* is the wavenumber. These formulas are valid for a small thickness conductor, which does not consider the skin effect, or for shield thickness minor of δ, the standard penetration depth definite as:

$$\delta = \frac{1}{\sqrt{\pi\mu\sigma f}} \quad . \tag{8}$$

In particularly, as the frequency of our analysis was of 50 Hz, $\mu = \mu_0$ and $\sigma = 36 * 10^6$ S/m, lead to δ = 11.2 mm.

A quantitative measure of a magnetic shielding effectiveness as mentioned in [4] is defined as :

$$SE_M^{dB} = 20 \log \frac{|B_0(r)|}{|B_T(r)|} \tag{9}$$

where B_0 is the magnetic induction without the shield at the observation point *r,* and B_S is the magnetic induction at the same point but with the shield applied.

III. SIMULATION AND EXPERIMENTAL RESULTS

In all simulations and in the experimental measurements, we have used a single circular wire with radius of 1.5 mm, excited by a sinusoidal current of 16 A which frequency of f = 50 Hz.

The results of the magnetic flux density of our theoretical model calculated according equations (4) are compared with the simulation results obtained by *Opera Vector Field* simulator, see Fig. 2, and with experimental measurements made with an electromagnetic field probe type Holaday HI. Fig. 3 shows these different results plotted together.

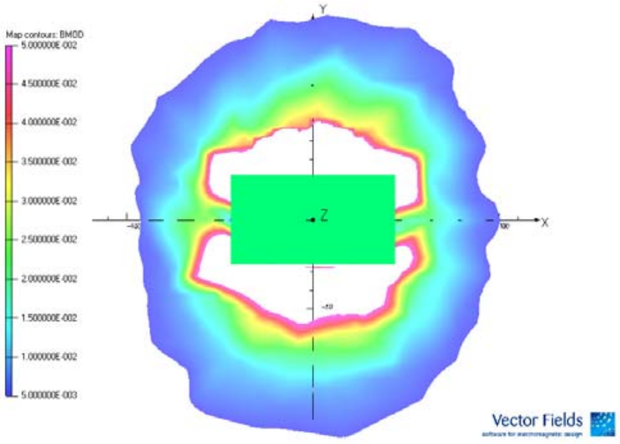

Figure 2. A simulation result obtained by *Opera Vector Field.*

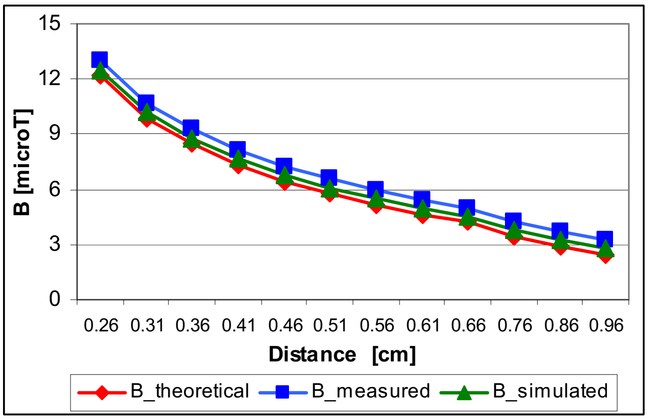

Figure 3. The results of the magnetic flux density of our theoretical model compared with the simulation results and with experimental measurements.

The good agreement of the results leads us to use the theoretical model to compare the experimental measurements of magnetic flux density, of an open shield of aluminum and of a steel SAE 1045 both with dimension of 1.5 m x 2 m, and thickness of 2 mm as show in Fig. 4.

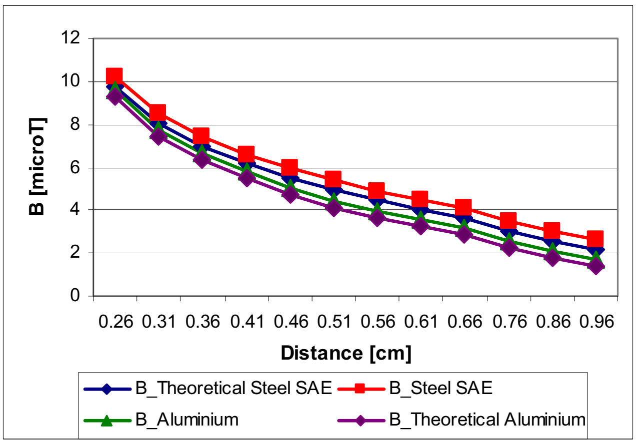

Figure 4. The results of the magnetic flux density of our theoretical model compared with open shield of aluminium and open shield of stell SAE 1045 .

Using the previous results the next step was to make a prototype of a three-layer structure obtained with an aluminum sheet and a steel SAE 1045 sheet, separated by an air-gap of 2 mm as shown in Fig. 5 (the air gap thickness is independent in the shielding efficiency values of the three layer screens).

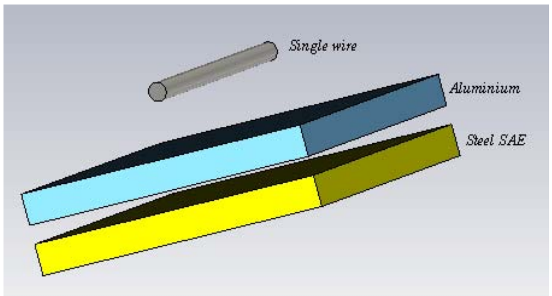

Figure 5. Layout of a three-layer structure made with an aluminum sheet and a steel SAE 1045 sheet separated by an air-gap of 10 mm.

These air–gap is usefull to isolate the conductor or nonmetallic screen from the ferromagnetic one avoiding a uniform distribution of eddy currents in a closed loops of induced current, always present and lying in planes perpendicular to the magnetic field vector due to the excitation source. In this way eddy currents generate a superimposing reaction field that reduces the overall magnetic flux helping the further mitigation executed by the ferromagnetic screen. The distance from screen and the wire conductor source was fixed at 15 mm. Source that has been maintained straight and parallel to the main plane of the shield, see Fig. 6 with adequate length able to guarantee the return of the wire to close the circuit (a wire loop) away from the shield.

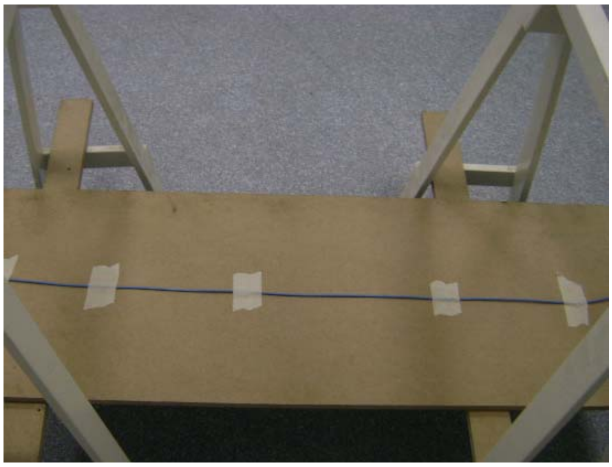

Figure 6. Wire source maintained straight and parallel to the main plane of the shield.

The magnetic field values were measured with an electromagnetic field probe type Holaday HI-3604 as show in Fig.7 along a perpendicular line to the main direction of the wire, and equally spaced with a steps distance of 5 cm.

Figure 7. Magnetic field measurements made with an electromagnetic field probe type Holaday HI-3604.

Naturally the distance of the magnetic field source in the experimental measurement of our frequency range, is such that we have considered the shield in the near field of the magnetic source.

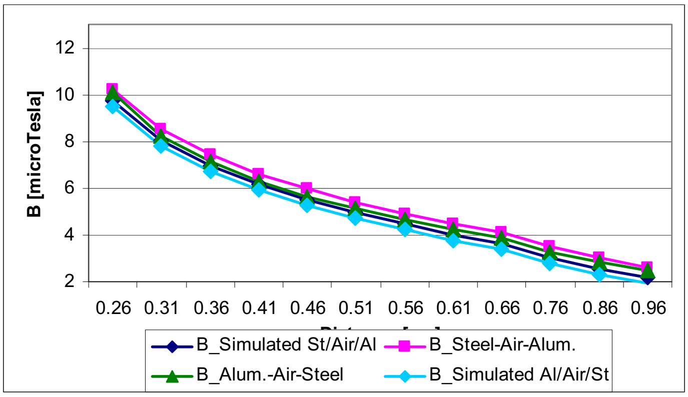

Figure 8. The simulation results and the experimental measurements of two prototype multilayer screen: aluminium/air/steel SAE and steel SAE/air/aluminium, compared whit theorethical multylayer model.

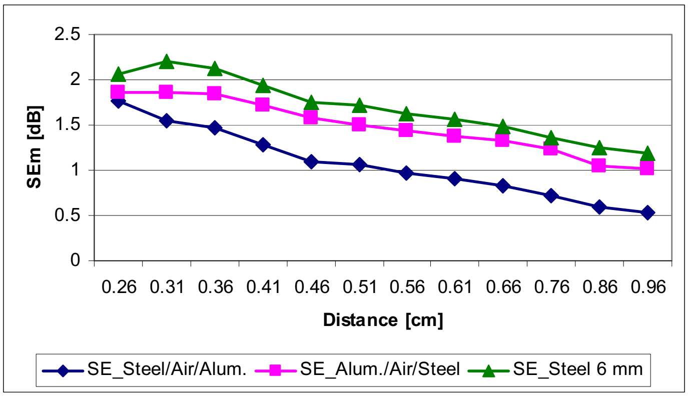

Figure 9. The experimental measurements of magnetic shielding efficiency of the two prototype multilayer screen: aluminium/air/steel SAE and steel SAE/air/aluminium, compared with experimental measurements of only steel SAE screen of 6 mm.

In Fig. 8 are shown the simulation results compared with the experimental measurements of the magnetic flux density of the two prototype of three-layer screen, composed by aluminum/air/steel SAE and steel SAE/air/aluminum.

Finally in Fig. 9 are shown the experimental measurements of the magnetic shielding efficiency of the two prototype of three-layer screen, composed by aluminum/air/steel SAE and steel SAE/air/aluminum compared with a single steel SAE screen of 6 mm of thickness.

As we can see the better solution to shield a magnetic field from a wire source with an open topology screen is to use a three-layer screen, composed by no-ferromagnetic (or conductor)/air/ferromagnetic material.

IV. CONCLUSION

We have presented some new geometric configurations for shielding magnetic fields at extremely low frequency (ELF), considering only the case of nonferromagnetic (or conductor) open shields.

To improve a magnetic field shield a simple analysis of 3-layer shield model of finite dimensions, containing non magnetic screen, air and steel SAE magnetic sheet, was made and described in this paper comparing the results with a theoretical model developed and shows in the paper using the Biot-Savart law.

The good agreement of the experimental measurements and theoretical data, allows us to use this design to improve the shielding performance of the magnetic screen for industrial frequency rate without increasing the amount of metal employed.

REFERENCES

[1] O. Losito, V. Dimiccoli, D. Barletta, "Magnetic Shielding Effectiveness of Multilayer Wire Mesh Screen" Proceeding of EMC Europe 2010, 13-17 September 2010, Wroclaw, Poland.

[2] S. A. Schelkunoff, ElectromagneticWaves. NewYork: Van Nostrand, 1943.

[3] E. Cardelli, A. Faba, and A. Pirani, "Nonferromagnetic Open Shields at Industrial Frequency Rate", IEEE Transactions on Magnetics, vol. 46, no. 3, March 2010.

[4] S. Celozzi, R.Araneo, G. Lovat, Electromagnetic Shielding, Wiley, (pp. 1-385), ISBN: 978-0-470-05536-6. Hoboken, NJ: Wiley Interscience, 2008.

[5] Guidelines for Mitigation Techniques of Power-Frequency Magnetic Fields Originated From Electric Power Systems, Task Force C4.204.

[6] B. A. Clairmont and Lordan, "3-D modeling of thin conductive sheets for magnetic field shielding: Calculations and measurements," IEEE Trans. Power Del., vol. 14, no. 4, pp. 1382–1393, Oct. 1999.

[7] P. R. Bannister, "New theoretical expressions for predicting shielding effectiveness for the plane shield case," IEEE Trans. Electromagn. Compat., vol. EMC-10, pp. 1–7, Mar. 1968.

[8] Y. Du, T. C. Cheng, and A. S. Farag, "Principles of power-frequency magnetic field shielding with flat sheets in a source of long conductors," IEEE Trans. Electromagn. Compat., vol. 38, no. 3, pp. 450–459, Aug. 1996.