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Shielding Improvement of Multilayer Enclosure at Low Frequency

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Abstract— **To shield low-frequency magnetic field is necessary to surrounding the entire 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. An adequate and cheaper possibility is the use of a multilayer screens. In this paper, we have investigated a simple way to design a multilayer shield obtained as inclusion of conducting shield enclosure and magnetic shield enclosure, in order to valuate the attenuation of the magnetic field generated by a loop antenna transmission at industrial frequency. We have simulated our multilayer shield model with Opera Vector Field® simulator, and compared the results with experimental shielding effectiveness measurements made on a prototype of the multilayer screens enclosure. 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

The magnetic field attenuation at extremely low frequency (ELF) in the last years is a subject of a growing interests especially towards magnetic fields produced by electric power systems, for the health effects upon human beings and for medical diagnostic applications as MRI [1] . 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 (reflection 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 full 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 a multilayer shield obtained as inclusion of two enclosure that in our work are a conducting shield enclosure and magnetic shield enclosure opportunely arranged, in order to assess the mitigation of the magnetic field generated in our case by a loop transmission antenna at industrial frequency rate. Our purpose was in fact to investigate only the case of shielding effectiveness of the double enclosure with a magnetic field source at industrial frequency rate (50 Hz) inside them. 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 simulated model of Opera Vector Field® simulator and its experimental data made on a simple prototype (aluminum enclosure, air gap, steel SAE enclosure) 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

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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 analyze the effect of magnetic field on a multilayer screen enclosure, 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.

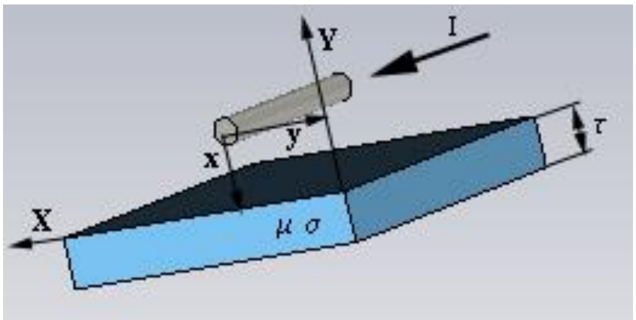

Figure 1. Layout of an ideal infinite plane to shield from a magnetic field generated by single wire of to develop the theoretical model.

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 (x_p, y_p) 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:

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

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_T is the magnetic induction at the same point but with the shield applied.

III. SIMULATION AND EXPERIMENTAL RESULTS

To reduce the overall material cost of the screen and its weight instead of a wide thickness of ferromagnetic enclosure to shield a magnetic field we have designed and realized two different box with different materials each one with thickness variable from 2mm to 4 mm. The external enclosure was realized with ferromagnetic material (steel SAE 1045) while the inner enclosure was realized with Aluminum as shows Fig. 2.

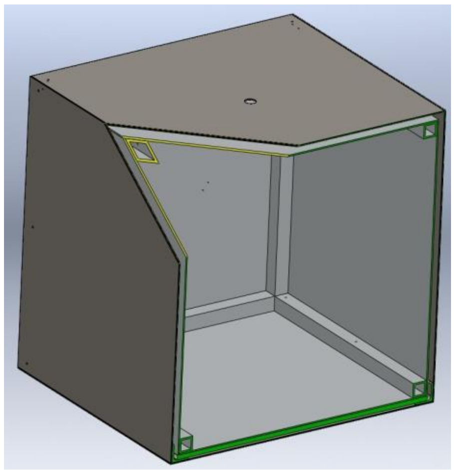

Figure 2. Layout and section of two different enclosure made with steel SAE 1045 (the external enclosure) and aluminium (interior enclosure).

The choice to realize the external enclosure as ferromagnetic material and interior enclosure as conductor material (if the source magnetic field is inside of the two enclosures) as described in [9] is due to the better performance of the “eddy current effect” that partially deletes the magnetic field of the source, if the conducting screen is the first screen intercepted by the source.

Source that in all simulations and experimental measurements, was a loop antenna with radius of 15 cm, excited by a sinusoidal current at frequency of f = 50 Hz inside the two enclosures as we can see in Fig. 3 and Fig. 4.

Moreover the air–gap between the two screen is useful 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.

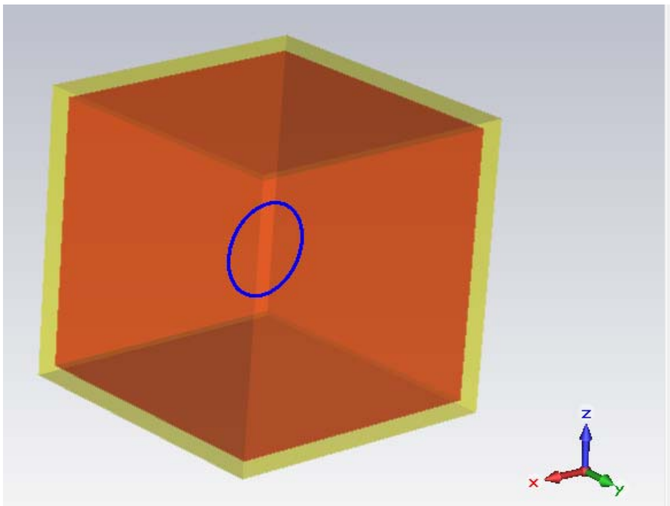

Figure 3. Simulation model of two different enclosures used in Opera Vector Field simulator.

The results of the simulation obtained by Opera Vector Field© simulator, were compared with experimental measurements made with a received loop antenna equal to the transmission loop antenna inside the enclosures, at different distance from external enclosure in x direction and y-direction as indicated by the axis shown in Fig. 3.

The complete set-up of the measurement system is shows in Fig. 5.

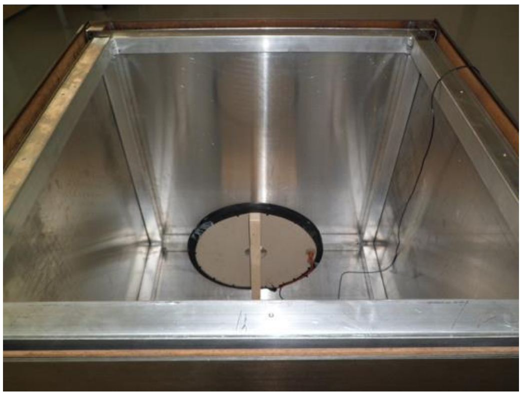

Figure 4. Transmission loop antenna inside of aluminium enclosure.

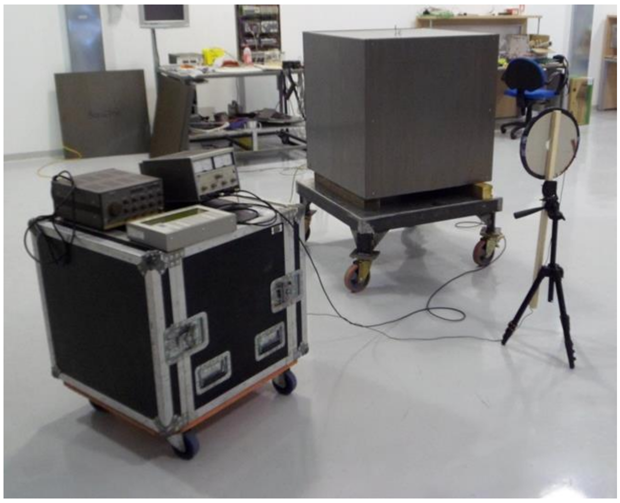

Figure 5. Shieldimg Set up measurements of the two enclosures.

In Fig. 6 and in Fig 7 we can see the simulation measurement compared with experimental measurement of the enclosure respectively of steel SAE of 4 mm, air gap of 20 mm. and aluminum of 4 mm. (Fig. 6), steel SAE of 4 mm, air gap of 20 mm. and aluminum of 2 mm. (Fig. 7).

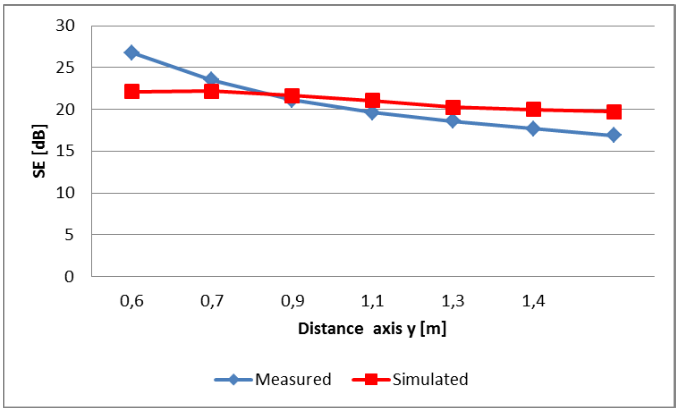

Figure 6. The results of the measured and simulated shielding effectiveness of two ecclosure: steel SAE 4 mm, air gap 20 mm., aluminium 4 mm.

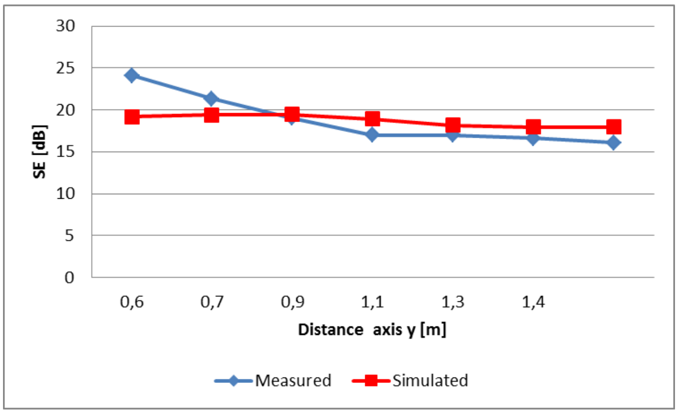

Figure 7. The results of the measured and simulated shielding effectiveness of two ecclosure: steel SAE 2 mm, air gap 20 mm., aluminium 4 mm.

As we can see from the results of Fig- 6-7, the increase of the steel SAE thickness produces a slight improvement of the shielding effectiveness. These lead us to consider the use of ferromagnetic screen enclosure with a thin thickness able to obtain a similar shielding effectiveness values of a wide thickness ones in order reduce the overall material cost of the screen and its weight.

This thickness reduction is possible thanks to the high values of the shielding effectiveness of conductor screen (aluminum of 2 mm of thickness) more than the shielding effectiveness of ferromagnetic material (SAE of 2 mm of thickness) as we can see from Fig. 8.

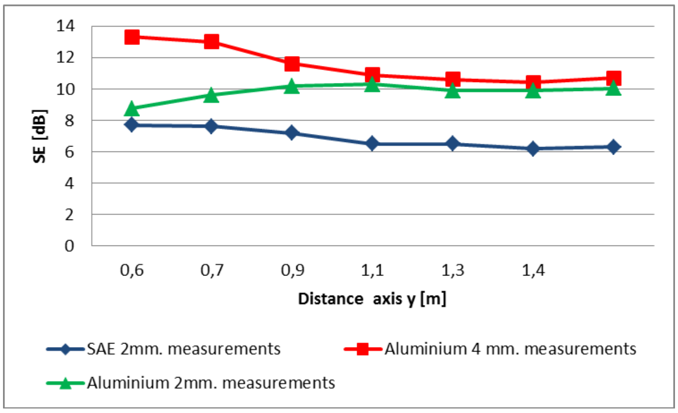

Figure 8. The experimental measurements of steel SAE enclosure of 2 mm (blu curve), aluminium enclosure of 4 mm (red curve) and), aluminium enclosure of 2 mm (green curve).

Therefore 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 a multilayer shielding enclosure for shielding magnetic fields at extremely low frequency (ELF), considering two shield enclosure respectively made with ferromagnetic (steel SAE1045) and conductor material (aluminum). To improve a magnetic field shield more simulations of shield enclosures separated by 20 mm of air gap was made with Opera Vector Field© and described in this paper comparing the experimental measurement of shielding effectiveness made on the prototype of enclosure screens. The good agreement of the experimental measurements and simulation 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.

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