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Numerical and experimental development of multilayer magnetic shields

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ABSTRACT

In this paper a detailed description of different passive shields for Extremely Low Frequency (ELF) applications is presented. The first part of the paper analyzes ferromagnetic and conductive materials by means of simulations and measurements. This step is mainly devoted to the identification of physical characteristics such as the relative permeability of the analyzed ferromagnetic materials. All the simulations are performed with a standard Finite Element (FE) code assuming linear behavior of the tested materials. The results are then used in the design of many shielding configurations and, finally, three different multilayer shield compositions are tested and presented. The second part of this paper outlines guidelines to assure a good shielding efficiency in the actual installation of a multilayer shield. The orientation of the shield as well as the possible decay of the shielding performance due to the discontinuity among the different slabs is investigated by means of experimental measurements. It is observed that the conductive part of the multilayer shield has to be faced to the source to have better performance. Moreover, it is important to assure the electrical conduction between the separate slabs. In this paper the conduction among different plates is conveniently obtained connecting them by straight bars of aluminum. In the third part of the paper the multilayer shield is tested under actual working conditions. A MV/LV substation was reproduced in the laboratory using a 630 kVA transformer working at its rated power. Several configurations were tested and the most significant results are presented. It is highlighted that, if the proper layout is not employed, the performance of the actual shield can be very different from the one of the material.

1. Introduction

Nowadays, the issue of human exposure to electric and magnetic fields is still of worldwide interest [1,2]. Several institutions have investigated this problem to accurately define the effect of electromagnetic fields on human health. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) claims that there is no evidence that prolonged exposure to electromagnetic fields produces possible long-term effects [3,4]. As a result, guidelines produced by ICNIRP have only focused on short term direct biophysical effects and cover the proper limits depending on the field frequency [3,4] or on the shape of pulsing magnetic field [5]. The safety requirements regarding the exposure to electromagnetic fields are usually divided into two categories: professional and public exposure. The main reference related to the professional exposure is the European Directive 2013/35/EU [6] that is strongly based on the ICNIRP guidelines [4]. The protection of the general public from the exposure to electromagnetic fields is less homogeneous because not all the states refers to the ICNIRP guidelines. Moreover, the states that decided to regulate the protection of the general public often adopted higher degree of safety by imposing stricter limits [2,7].

For the above reasons the emissions of the electrical infrastructures for electricity distributions need to be analyzed. These systems are operated at Extremely Low Frequency (ELF), i.e. 50/60 Hz. Frequently, the electric field values are lower than the applicable limit while the magnetic field levels often exceed the admissible values. The current literature has well explored the possible mitigation solutions for power lines identifying several options that are suitable for overhead [8,9] and underground installations [10,11].

Finally, it is also important to consider the emissions related to the secondary electrical substations. The transformation of the medium voltage (MV) into a low voltage (LV) by means of a transformer is accompanied by a local increase of the current values on the LV side. Therefore, in the surrounding volume of the substation the magnetic field level is always higher than the average and it is often necessary to employ a mitigation system [12,13].

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The main components of a substation are: MV cables supplying the substation, MV and LV connections between the transformers and the respective MV and LV switchboards, the MV and LV switchboards and MV/LV transformers. The LV connections, the transformer (especially the cast resin ones) and sometimes the LV switchgear are the most crucial on magnetic field generation. Mitigation of magnetic fields can be done in various ways based on two techniques: optimal displacement of sources and application of screening systems (passive or active).

In this paper we analyze multilayer passive shields. The first part analyzes the following shielding materials: pure iron, grain oriented iron and aluminum. All the materials are tested by means of simulations and experimental measurements. This step is mainly devoted to the identification of physical characteristics such as the relative permeability of the analyzed ferromagnetic materials. As far as the simulations are concerned, a Finite Element code is used [14] and all the material characteristics are assumed to be linear. After the material characterization, an extensive simulation campaign was carried out in order to test different configurations. Three multilayer compositions are selected in order to fulfill the most common mitigation requirements in substations. These compositions were realized and tested experimentally.

The second part of the paper deals with the analysis of the possible decay of the shielding performance related to the assembly of the actual shield. Particularly, the effect of discontinuity among the different slabs was examined. A possible solution to the problem that was identified by means of an experimental approach is presented and discussed.

In the third part of the paper the multilayer shield is tested under actual working conditions. A MV/LV substation was reproduced in the laboratory using a 630 kVA transformer working at its rated power. Several configurations were tested and the most significant results are presented.

2. Design of passive shields

Passive shields are usually made of ferromagnetic material with high permeability and/or conductive material with high electrical conductivity. A ferromagnetic material reduces the magnetic flux density in a shielded area through the flux lines deviation [15,16]. Usually, isotropic or grain oriented ferromagnetic laminations similar to those adopted in the electrical machine industry are used [17].

The working principle of conductive shields is based on the Faraday's law. The time varying magnetic field produced by AC sources induces eddy currents inside the shield and, consequently, they generate an additional field that reduces the magnetic field produced by the sources. Usually, the conductive shields are made of copper or aluminum, the latter is often preferred because of its lower specific weight.

Assuming that the screen is interposed between the source and the shielded area, the shielding efficiency can be quantified by different parameters. Here we make use of the *Shielding Effectiveness* (SE) that is defined as

$$\mathrm{SE}(P) = 20\log\frac{B_0(P)}{B_s(P)} \quad (1)$$

being $B_0(P)$ and $B_s(P)$ the magnetic flux density at a given point P in the absence and in the presence of the shield, respectively. The SE is expressed in dB.

The SE of ferromagnetic material is very high close to the screen (on the side of the shielded area), however, it decreases quickly moving away from the shield. Differently, a conductive material provides a smaller SE close to the screen. The advantage is that the decrease of the SE value with the distance is smaller. For this reason, the conductive material is often preferred for open shield configurations. This is important in substations because they cannot be locked inside a closed box without an entrance, hence, an open shield configuration is always employed. Finally, the combination of ferromagnetic and conductive sheets provides good performance at varying distance from the shielding system [18].

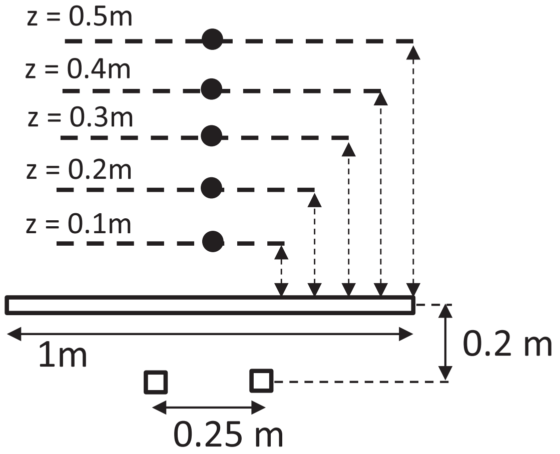

Fig. 1. Cross section of the test layout: a circular coil with diameter equal to 0.25 m is placed below the metallic square slab. Five field points are defined in the shielded region. The coil is regulated in order to test the shield at two different magnetic field level: 10 and 100 μT.

Prior to design a shielding system it is required a material characterization based on comparison between experimental results and numerical simulations. A proper setup was created in order to provide such comparison. As shown in Fig. 1 a magnetic source composed by a circular coil was realized in order to create at the center of the shield a magnetic flux density of 10 and 100 μT (medium and high value for ELF magnetic flux density). The test procedure evaluates the performance of the screen for different distances from the shield. Five inspection points were defined according to Fig. 1. The magnetic field is measured by means of a commercial instrument endowed with an isotropic probe whose frequency range is 5 Hz–100 kHz.

The simulation of a shielding system requires the solution of the Maxwell equations. Analytical methods can be efficiently employed only for very simple geometries [19,20] or when particular conditions are satisfied (e.g. proper frequency range) [15,21–25]. Conversely, when the geometry is more complicated a numerical approach must be adopted. Several techniques are available for the solution of field problems, however, some issues could arise when dealing with thin slabs of metallic materials. For instance, for 3D problems the standard Finite Element Method (FEM) can lead to a mesh with high number of unknowns and numerical instabilities, and it is also known that the Boundary Element Method (BEM) cannot provide accurate solutions when the domain for analysis is too thin [26]. These problems can be overcome by means of integral formulations [27–29]. In this paper we highlight that a 3D analysis can be avoided. The geometry represented in Fig. 1 can be easily approximated by a 2D axisymmetric model that is handled by a free finite element code [14] that provides magnetic flux density distributions for DC and AC sources. The simulations are aimed to verify or identify the actual properties of the shielding materials. This procedure was unavoidable because the magnetic permeability of ferromagnetic material as isotropic or grain oriented iron is not provided by the manufacturer for very low values of applied field (10 and 100 μT).

2.1. Ferromagnetic shields characterization

The identification of the relative permeability was performed in the case of one pure iron sheet with thickness of 0.5 mm. As