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On the use of TEM cells for the calibration of power frequency electric field meters

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ABSTRACT

This paper focuses on the performances of TEM cells when used in the calibration of power frequency environmental electric field meters. The spatial non-uniformity of the electric field inside a TEM cell is analyzed through experimental investigations and three-dimensional Boundary Element modeling to evaluate the field experienced by the sensing elements of actual 3D meter probes. The perturbation caused by the probe support is also taken into account. The uncertainty component associated with the spatial non-uniformity in the volume taken up by typical power and low frequency field probes is estimated. The field non-uniformity is also evaluated in relation to the use of TEM cells of reduced size. Finally, the field non-uniformity is exploited to predict the performance of an actual field meter operating in significant field gradients.

1. Introduction

TEM cells are the recommended set-up for the generation of reference electric fields used in the calibration of probes and sensors in the frequency range from some kilohertz to hundreds of megahertz. A wide literature, see for example [1,2], analyses in detail their behavior and relevant standards precisely define the rules and procedures for a correct execution of the calibration process [3,4] in the specified frequency range.

As concern the calibration of power frequency field meters, used for the measurements of environmental fields in the evaluation of human exposure, the recommended configuration is the parallel plate systems [5–7]. The uncertainty associated with the generated field ranges from a few part per thousand to a few percent. Nevertheless, TEM cells are very often used as an alternative generation system. With respect to the recommended devices, TEM cells have some practical advantages such as: (i) the possibility of working in a wide frequency range (from DC up to some hundreds megahertz), (ii) the reduced size, (iii) the improved immunity from external disturbances, due to the intrinsic shielding, and the reduced disturbances which can cause interference with other devices. On the other hand, due to their shape, TEM cells show lower electric field uniformity with respect to parallel plate generation systems of the same size. An increase of the cell size improves the field uniformity, but at the same time limits its cutoff frequency. Thus, the possibility of using the cells for the generation of reference electric fields both at high and low frequencies needs a compromise between these two opposite requirements.

The paper aim is a quantitative analysis of the performances of a TEM cell, when used in the calibration of electric field meters, which are employed for the measurements of environmental power frequency fields. So, reference is made in the following to the indications given by the relevant standards [5,6].

In comparison with the radiofrequency ones, the low and power frequency field probes are generally characterized by greater dimensions and different internal sensor

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arrangements. The non-uniformity of the spatial field distribution inside the TEM cell and its effect on the indication of the electric field meters under calibration are then investigated. The spatial field distribution inside the cell can be evaluated numerically (e.g. by the moment method as detailed in [8]) or experimentally, by means of calibrated field probes. In the following, a noncommercial three dimensional tool based on the Boundary Element Method (BEM) is adopted to compute the field distribution actually experienced by three-dimensional field probes. In this analysis the probe characteristics (dimensions, number and different arrangement of the field sensing elements) and the possible presence of dielectric material (e.g. probe support) are accounted for. The validation of the computational model is performed by comparison with analytical solutions and experimental data. The measurements are performed in a TEM cell, available at the Istituto Nazionale di Ricerca Metrologica (INRIM).

Different configurations are analyzed, such as open or closed cell and field probe placed in the upper or lower section of the cell. An estimation of the size averaging error, which arises because of the non-negligible dimension of the field sensing elements when the probe is introduced in a non-uniform field, is also taken into consideration. Moreover, some comparisons with a parallel plate system are presented.

A further effect investigated is the presence, during the calibration, of the field probe support, which can significantly influence the distribution of the electric field in the volume taken up by the meter probe [9,10]. In fact, calibration should be performed in the same configuration used during the measurement, that is with the probe equipped with its own support. In practice, because of their length dielectric supports different from those adopted during the on-site measurements are generally used in the calibration phase.

On the basis of the results obtained, an evaluation of the uncertainty contribution that can be associated with the field non-uniformity is carried out, taking into account the finite dimensions and internal field sensors arrangements of actual 3D probes in relation to the TEM cell dimension.

Finally, the field non-uniformity of the TEM cell is exploited to estimated the error made by the field meter when used in presence of significant spatial field gradient.

2. Numerical model and experimental setup

Under the assumption of quasi-stationary operating conditions, the electric field formulation is developed in an open boundary 3D domain, where the conductive bodies are replaced by Dirichlet conditions, imposing the known potential on the electrodes. This hypothesis allows the description of the electric field $\boldsymbol{E}$ in terms of a scalar potential φ ($\boldsymbol{E} = -\text{grad}\ \varphi$), which leads to the boundary value problem:

$$div(\varepsilon \text{grad} \varphi) = 0 \tag{1}$$

Eq. (1) is solved by means of a standard BEM approach. The surfaces of the bodies included in the domain are divided into N triangles. In each element the potential is assumed to be linear and its normal derivative to be constant. The electric field distribution is computed by solving the resulting BEM equation in the internal and external regions:

$$\zeta\varphi_i = \sum_{j=1}^{N}\left[(\nabla\varphi\cdot\mathbf{n})_j\int_{\Omega_j}\psi ds - \varphi_j\int_{\Omega_j}(\nabla\psi\cdot\mathbf{n})_j ds\right] \tag{2}$$

where Ω_j are the triangular elements, $\psi = 1/4\pi r$ is the 3D Green function (being r the distance between source point i and computational point j), $\boldsymbol{n}_j$ is the normal unit vector and ζ is 0.5 on the surfaces and 1 elsewhere. The unknowns are the nodal values of the potential and its normal derivatives in each triangle on the surface of the dielectric body (e.g. dielectric support); on the electrodes the only unknowns are the normal derivatives of the potential, while the imposed potential represents the field source. Problem (2) is completed by the interface conditions between internal (a) and external (b) volumes:

$$\begin{cases} \varphi_j^{(a)} = \varphi_j^{(b)} \\ \varepsilon^{(a)}\left(\nabla\varphi^{(a)}\cdot\mathbf{n}^{(a)}\right)_j = -\varepsilon^{(b)}\left(\nabla\varphi^{(b)}\cdot\mathbf{n}^{(b)}\right)_j \end{cases} \tag{3}$$

The analysis is developed considering the INRIM TEM cell shown in Fig. 1a, where the origin of the coordinate system is assumed in the central point of the septum. The cell has a square cross-section of side L_T = 1.2 m in the xz-plane with a shell-septum distance D_T = 0.6 m (ratio L_T/D_T = 2) and a 2.4 m length along y-axis. The cutoff frequency of the TEM cell, when used for radiofrequency calibrations, is about 125 MHz. A 60 V, 50 Hz voltage, generated by a calibrated voltage source (Fluke 5500A Calibrator), is applied across the electrodes (septum and shell), which corresponds to a nominal value E_0 of 100 V/m in the centre of the lower half-cell P_0 (0, 0, −0.3 m) or in the centre of the upper half-cell Q_0 (0, 0, +0.3 m). Taking into account the considered frequencies, the magnetic field can be disregarded, since the load terminal of the TEM cell is open.

The INRIM parallel plate system, considered for the comparison, is composed of two aluminum square horizontal plates of side L_P = 2 m at a vertical distance D_P = 1 m (ratio L_P/D_P = 2); five grading rings improve the field uniformity in the central volume between the plates [11].

The choice of the most suitable BEM discretization of the TEM cell, as a compromise between accuracy and computational cost, is made by increasing the number of triangles in the system of Fig. 1b and by comparing the computed field values in different points of the domain. The obtained results, summarized in Table 1, show that a mesh with about 9700 surface elements is surely sufficient to make the discretization error negligible. The limit error due to the numerical evaluation of the electric field values in the central volume of one half-cell is estimated to be within ±0.5%; it is obtained by considering, besides the discretization error, the comparison with analytical solutions [10,12].

The measured data are obtained using a free-body electric field meter, previously calibrated in the parallel plate generation system. The meter is equipped with a 3D cubic