Calibration methods for a large loop antenna measurement system

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Abstract — A hybrid approach concerning the calibration and evaluation of a loop antenna suitable for dipole and quadrupole identification is presented. The main aspects concerning the mutual influence of the loops are considered and emphasized, in particular, when the complete measurement setup is utilized. Analytical and numerical methods are applied. The methods were validated by the available experimental and theoretical results, at the 60 kHz-180 kHz frequency range.

I. Introduction

Equivalent radiated emission sources for evaluating the contribution of electric and electronic equipments to electromagnetic environments are useful for electromagnetic compatibility studies. Some methodologies can be applied for this purpose, like numerical modeling and measurement techniques. Among them, the measurement techniques using large coils placed around the equipment under evaluation can be mentioned [1]-[3]. This approach allows achieving an integration of the magnetic flux density, reducing the constraints related to field sensor positioning inaccuracies. For example, to measure the dipole component of a multipole expansion, the standard CISPR 16-1 recommends an antenna configuration that uses three orthogonal loops, the so-called Van Veen and Bergervöet antenna [3]. In this paper, a prototype of an antenna, initially built for dipole and quadrupole identifications is considered. Its measurement principle is similar to a spatial filtering since each coil sensor is sensitive to one specific component of the multipole expansion [4]-[6]. The design characteristics and the theoretical aspects are presented in detail in [5]. Here, we present a hybrid approach concerning the calibration and evaluation of these specific configurations of loop antennas. The flux concatenated by each loop, which corresponds to the contribution of each multipole expansion component (dipoles and quadrupoles), is carried out based on analytical, numerical and experimental results. Since the inaccuracy of the measurements can strongly influence the determination of each term of the multipole expansion, the proposed methodology takes into account the complete set of antennas, instead of adopting partial arrangements of loops. The influence of the loop arrangement mutual effects to the antenna performance and calibration is analyzed.

II. The Prototype Antenna

Fig. 1 shows the prototype antenna with its loop arrangements corresponding to the dipole (2 loops for the dipole component A_{10}), the quadrupole (2 loops for the quadripole component A_{20}) and the loop from the standard CISPR16-1. All mentioned loops were built initially only in the z-direction. The complete measurement setup is surrounded by a sphere of radius (r_M) equal to 0.225m. The short circuited loops were proposed as sensors with a flat response within the 9 kHz - 30 MHz frequency range. Although the use of short circuited loops corresponds to a simple solution, the magnetic coupling between them imposes some constraints to the measurement and calibration methodology.

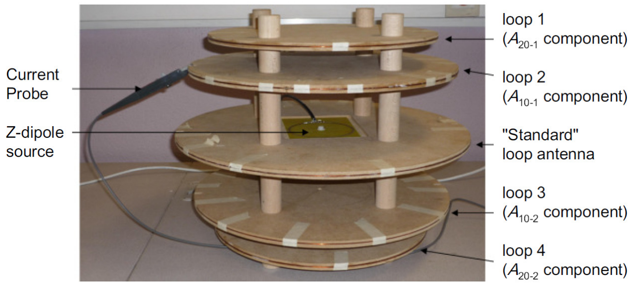

Fig. 1. Prototype Antenna (‘A_{10}’, ‘A_{20}’ and ‘standard’ loops)

Based on the multipole expansion of the magnetic field, the relationship between the fluxes across the surface delimited by the “sensor set” and A_{nm} components of the expansion can be directly obtained [5],[6]. The quasi-static approximation was adopted, and for the maximum frequency of 30 MHz, it is valid for a $r_M \leq$ 1.7m. In our case, assuming the expansion limited to the second order and the z direction (m=0), it is obtained [6]:

$$\begin{pmatrix} A_{10} \\ A_{20} \end{pmatrix} = K\,\phi^A = \begin{pmatrix} 0 & e_1 & e_1 & 0 \\ e_2 & 0 & 0 & -e_2 \end{pmatrix} \begin{pmatrix} \phi_1^A \\ \phi_2^A \\ \phi_3^A \\ \phi_4^A \end{pmatrix}, \tag{1}$$

$$e_1 = \frac{10^8 r_M}{32\pi} \quad e_2 = \frac{6125.10^4 r_M^2}{9\pi\sqrt{7}}, \tag{2}$$

where ϕ_i^A denotes the flux through the 1-turn loop antenna A_i given by Fig. 1, without currents in the loop antennas.

III. Calibration of the Antenna

Each loop antenna (i=1,4) being short-circuited[1], the equation between the measured current I_i and the flux ϕ_i embraced by the loop (different of ϕ_i^A) is given by:

$$r_i I_i + i\,\omega\,\phi_i = 0\,. \tag{3}$$

[1]The theoretical expressions are proposed here *without* the standard loop. Its introduction makes the presentation less readable even if the principles remain the same.

The flux part only due to the currents I_j is obtained by using the matrix M of the proper and mutual inductances:

$$(\phi_i-\phi_i^A)=\sum_j M_{ij}I_j \;. \qquad (4)$$

Gathering (3), (4) and (5) it is obtained (k=1, 2):

$$A_{k0}=\sum_i K_{ki}\phi_i^A=\sum_i K_{ki}(\phi_i-\sum_j M_{ij}I_j)=-\sum_{i,j}\frac{K_{ki}}{j\omega}Z_{ij}I_j \;, \qquad (5)$$

where $Z_{ii} = r_i+j\omega L_i$ and $Z_{i\neq j}=j\omega M_{ij}$. This equation links the sought coefficients A_{k0} to the 4 measured currents:

$$A_{k0}=\sum_i Z_{ki}^A I_i \;\text{ with: }\; Z_{ki}^A=\frac{-1}{j\omega}\sum_j K_{kj}Z_{ij} \;. \qquad (6)$$

Z^A is a rectangular matrix with only 4 distinct terms, because of the structure of K and of the symmetries of the loop system:

$$Z^A=\begin{pmatrix} a & b & b & a \\ c & d & -d & -c \end{pmatrix}. \qquad (7)$$

These 4 terms can be calculated analytically based on the geometrical dimensions of the loops: we call this method “computed calibration” of the sensor with several loops.

The second calibration method is experimental. The currents are measured for 2 independent and known sources: a dipole (a_{10}, 0) and a quadripole (0, a_{20}) which are located in the center of the loop system. The 8 measured values are denoted by $I^{(1)}$ for the dipole source and by $I^{(2)}$ for the quadripole source; they enable to forecast the currents $I^{(b)}$ for every other source combination (b_{10}, b_{20}) by using a matrix $Y^{(a)}$ such that:

$$I^{(1)} = Y^{(a)}(a_{10},0)^T \text{ and } I^{(2)} = Y^{(a)}(0,a_{20})^T;\; I^{(b)} = Y^{(a)}(b_{10},b_{20})^T. \qquad (8)$$

This matrix $Y^{(a)}$ has the simple following form:

$$\begin{pmatrix} I_1^{(b)} \\ I_2^{(b)} \\ I_3^{(b)} \\ I_4^{(b)} \end{pmatrix}=\begin{pmatrix} I_1^{(1)}/a_{10} & I_1^{(2)}/a_{20} \\ I_2^{(1)}/a_{10} & I_2^{(2)}/a_{20} \\ I_3^{(1)}/a_{10} & I_3^{(2)}/a_{20} \\ I_4^{(1)}/a_{10} & I_4^{(2)}/a_{20} \end{pmatrix}\begin{pmatrix} b_{10} \\ b_{20} \end{pmatrix}. \qquad (9)$$

The experimental calibration coincides with the inverse relation of (9). It is then required to build a measured estimate $Z^{(a)}$ of the matrix Z^A, which enables as in (6) to determine the source (b_{10}, b_{20}) corresponding to the measurements $I^{(b)}$:

$$b_{k0}=\sum_i Z_{ki}^{(a)}I_i^{(b)} \;. \qquad (10)$$

As the matrix $Y^{(a)}$ is not squared, the matrix $Z^{(a)}$ is computed using a least-square method:

$$Z^{(a)}=(\overline{Y^{(a)T}}\,Y^{(a)})^{(-1)}\,\overline{Y^{(a)T}} \qquad (11)$$

This leads to:

$$b_{10}=\frac{a_{10}}{\|I^{(1)}\|^2}\left[\overline{I_1^{(1)}}(I_1^{(b)}+I_4^{(b)})+\overline{I_2^{(1)}}(I_2^{(b)}+I_3^{(b)})\right], \qquad (12)$$

$$b_{20}=\frac{a_{20}}{\|I^{(2)}\|^2}\left[\overline{I_1^{(2)}}(I_1^{(b)}-I_4^{(b)})+\overline{I_2^{(2)}}(I_2^{(b)}-I_3^{(b)})\right]. \qquad (13)$$

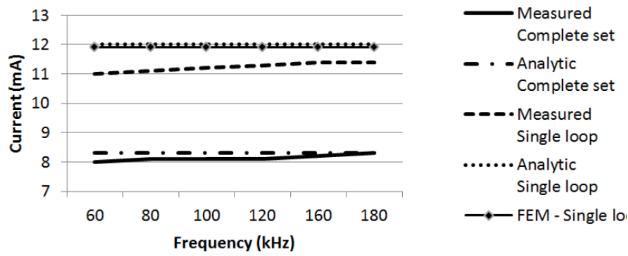

Fig. 2. Comparison of current values on the A_{10} loop for the complete antenna and single loop setups.

The dipole component is thus a weighted sum of the average of the currents in the symmetric loops (1-4 and 2-3), and the quadrupole component is based on the differences of the same currents. The structure of the matrix is of course the same than in (7).

IV. FIRST RESULTS AND PERSPECTIVES

The first measurements confirm the convergence between both calibration approaches, computed and experimental (Fig. 2): the currents *computed* analytically or by the finite element method, or *measured*, by the calibrated excitation of the antenna (short-circuited loops alone or full system on a known dipole source, I=1A and r=5cm) are in agreement. It means that the measured currents and the analytic model provides the “correct” dipole component using (7) or (12). Note that the mutual influence between short-circuited loops cannot be neglected for the complete set: the differences between the complete set and the single loop can be up to 50%.

The full tests for the measurement of the dipole and quadrupole components of a complex system will be presented in the extended version of this work.

V. ACKNOWLEDGMENT

This work was partially supported by the Capes-Cofecub (09/0568) and O2M projects.

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