New robust coil sensors for near field caracterization

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***Abstract*— This paper introduces a new generation of magnetic field sensors, based on the spherical harmonics decomposition concept. The measurement principle is similar to a spatial filtering: according to the coil shape, the sensors are just sensitive to a specific component of the multipolar expansion. Five coil shapes are determined, in order to account for the first two orders of the harmonic decomposition. The way of determining the coil shape is first explained, and a validation is proposed using a finite element software.**

Keywords– Coils electromagnetic sensors, near field measurements, multipolar expansion, radiated EMC, radiated electromagnetic sources characterization

I. Introduction

With the increase of power density in modern power systems, interactions between various elements become often a key point to be addressed. This problem can be treated at various scales: interactions between two variable speed drives or power transformers in the same room ("indoor EMC"), interactions between power and control board, or different devices on the same board. On this latter example, magnetic coupling between magnetic components (inductor, transformer) and/or wires are encountered in complex systems, which can lead to dysfunctions or a bad filtering.

Addressing these magnetic coupling implies the ability of magnetic field characterization, close to the sources. The complete knowledge of this near field can be based on simulation or experimentation, but is unavoidable to handle interaction problems.

The first idea starts from a simple mapping of the near magnetic field, using some magnetic sensor and sampling the space by moving the sensors around the system, or by moving the system itself, or by multiplying the sensors, or using any appropriate combination of all previous solutions.

After this step, the magnetic field is characterized by a set of thousands of measurement points (obtained from experimental or simulation data), what is very heavy for interaction studies. These data must therefore be summarized into a simpler equivalent source [1-3].

One possible method is to use multipolar expansion [1-7], which has shown previously its ability of synthesizing any magnetic sources into known standardized sources (dipole, quadrupole, etc.). For instance, it has been shown that a set of several thousands of data points can be summarized into 15 terms, with a large validity region [1].

The determination of each term of the multipolar expansion consists in solving an "inverse problem", and may be very sensitive to measurement/simulation inaccuracy. Several solutions can be used to reduce the effect of this inaccuracy [2]. The idea presented in this paper is to imagine specific sensors, to measure directly the component of the multipolar expansion. The shape of the sensors will be designed in order to be sensitive to one term only, what should increase the accuracy of the parameter determination [3-7].

The paper will be organized as follows:

- Presentation of the mathematic model : spherical harmonics decomposition
- Design of the sensor geometry
- Validation with a finite elements software [11]

II. Spherical Harmonics

The multipolar expansion is a classical tool used for the electromagnetic field representation [8-10]. It allows decomposing any field into an infinite sum of simple terms. The first order of the decomposition is the well known dipole. Several mathematical functions (basis) can be used for the decomposition. For near field studies, the quasi-static approximation is suitable, therefore, displacement currents can be neglected. This decomposition is thus simpler than using the complete one, including propagation terms [8].

A. Harmonic decomposition

Outside a sphere including all radiation sources, the magnetic field can be completely described with its magnetic scalar potential $\psi(t)$. This potential is a solution of Laplace equation:

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$$\Delta\Psi(t) = 0 \quad (1)$$

Considering harmonic decomposition of the temporal sources leads to complex variables. Then, the solution of (1) can be expressed as follows:

$$\begin{cases} \vec{B}(r,\theta,\varphi) = -\overrightarrow{grad}(\Psi) \\ \Psi(r,\theta,\varphi) = \sum_{n=1}^{+\infty} \sum_{m=-n}^{+n} A_{nm} \cdot \frac{1}{r^{n+1}} \cdot Y_{nm}(\theta,\varphi) \\ \vec{B}(r,\theta,\varphi) = \sum_{n=1}^{+\infty} \sum_{m=-n}^{+n} \vec{B}_{nm} \end{cases} \quad (2)$$

Where:

- Y_{nm} are specific functions called spherical harmonics,
- *r*, the distance between the centre of the decomposition and the point where the field is expressed,
- $\vec{B}_{nm} = -\overrightarrow{grad}(A_{nm}.r^{-(n+1)}.Y_{nm}(\theta,\varphi))$, the elementary magnetic field of the decomposition,
- A_{nm}, the coefficients of the decomposition, the unknowns.

B. Relevance

The choice of this basis is motivated by two reasons. First, the orthogonality: coefficients A_{nm} are unique for a given source. Secondly, the $r^{-(n+1)}$ decrease of the different terms insures a hierarchy between all parts of the decomposition: The larger the distance to the source is, the less terms are necessary to reconstruct the field. Far from the source, only the dipole is useful to fully characterize the radiated field.

For interaction studies, we have decided to limit the expansion to the two first orders of the decomposition. This also corresponds to the physical behaviour of most sources in electrical systems, where disturbances often originate from current loops. Therefore, the number of unknowns is limited to only 8 (from (2), there are *2n+1* coefficients for each order n. Thus, 3 unknowns for order 1 and 5 for order 2).

The aim of the identification is thus to deduce these 8 unknowns from measurements achieved around the radiation source. For this purpose, one possible solution is to take advantage from the fast decrease of the high order terms with the distance: far from the source, the sensors are only sensitive to the dipole. This property has been used in [4-7]. This lead to large measurement systems, and furthermore, the accuracy is poor: far from the Device Under Test, the field is low, and the signal is small. Thus, in the following section, the design of specific sensors will be proposed. Instead of employing the $r^{-(n+1)}$ behaviour, the aim is to use the geometrical properties of the spherical harmonics functions Y_{nm}. This will be explained in the following section.

III. SENSOR DESIGN

To determine the 8 unknowns, a first idea may be to start from a set of several measurement points, using either a single measurement loop, or several ones. Then, a linear system can be solved to compute the 8 values from these multiple measurements, using inverse problem methods (error minimization or any other method). The advantage of this solution is the simplicity of the sensors, however, the convergence and final accuracy is not guaranteed, especially if the spatial sampling is not suitable (number and special position): the matrix condition number can often be very poor [2].

We have chosen to use less sensors (8 to determine the 8 unknowns), but designed in order to give more robust information. The difficulty is to find a shape which is not sensitive to any other component than the one which has to be determined. To clarify our approach, we propose to detail the process of creating a B_{10} sensor. Starting from the observation of the magnetic field created by a simple B_{10} source (all A_{nm} = 0 except A_{10}, e.g. a dipole oriented along z axis), we look for the basic shape which maximizes the B_{10} flux (Fig. 1). The result is obviously a simple loop, as presented in previous works [4-6]. Then, substituting to the B_{10} source a more complex one, we try to define a new shape, more robust against the other terms of the field. This new source is obtained by imposing all A_{nm} to 1, until n=4 (24 coefficients). This order has been considered sufficient for most of practical radiating systems, at reasonable distances (not too close). We try to define the position of a loop (or a combination of loops), which cancel all the other contributions of magnetic field. For various z position of a simple loop, it is clear from Fig. 2 that only 4 elementary magnetic fields among 24 bring a contribution to the flux. To cancel the odd components (B_{20} and B_{40}), the idea is to use a second loop, symmetrical from the first one, as illustrated on Appendix. After composition of the two fluxes, only B_{10} and B_{30} remain.

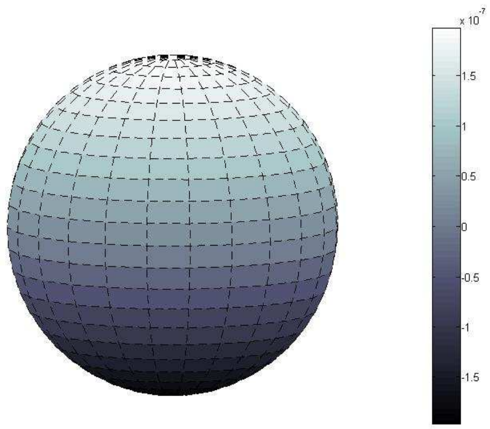

Figure 1. Radial component of induction (T) for a B_{10} source.

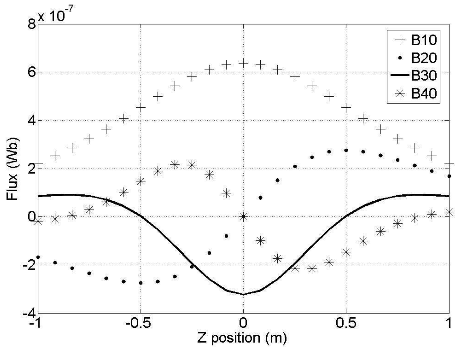

Figure 2. Flux induced in the loop sensor (radius 1 meter) as a function of z, for each component of **B**

Choosing a proper distance between the two loops finally allows cancelling the contribution of B_{30} (Fig. 2). This is obtained for a distance $z = R = r \cdot 2/\sqrt{5}$, where R is the radius of the loops and z the inter-loops distance. This geometry is exactly a Helmholtz coil [7].

In comparison with previous works [4-6] it is clear from Fig. 2 that this new sensor is far more robust versus parasitic components: a single loop in z=0 measures both B_{30} and B_{10}…

Using the same method allows determining the shape of all other sensors (see Appendix):

- 1st finding a generic shape to maximize the flux of the tracked component
- 2nd Modifying the geometry and combining several shapes to reject the other components

IV. FEM Validation

To validate the method, a toroidal inductor has been used (5 cm diameter - Fig. 3). It corresponds to the common mode filter at the input of a variable speed drive. The aim is to determine the coefficient of the spherical harmonic decomposition. We have included the identification of the first and second order of the decomposition (all 8 sensors). Since we are looking for the field outside the variable speed drive, we identified the coefficients A_{1m} and A_{2m} outside a validity sphere of 30 cm radius, corresponding to the double of the size of the apparatus. The inductor is disposed at the center of the sphere. All tests have been carried out in a Finite Elements Software FLUX3D© [11].

a. A_{1m} identification and validation

The validation of the dipole identification is shown

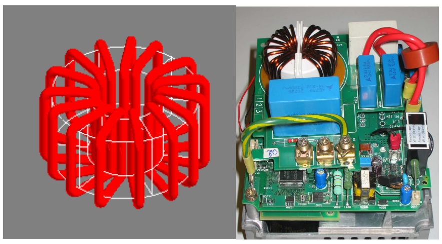

Figure 3. Toroidal inductor and the associated variable speed drive

on Fig.4. After identification including 1 or 2 orders, we compared the reconstructed magnetic field with the FEM results, from 1 m to 2 m. First, in all cases, the good concordance validates the 8 A_{1m} and A_{2m} values. Far from the source the difference is smallest since the dipole is preponderant. Second, the results confirm the interest to make identification until the second order: on Fig.4, the convergence is better with the source including dipole and quadrupole.

b. Identification and robustness

First, we checked the robustness of the sensor to a change of radius *r:* three different sensors for three different measurement distances have been tested, the identification has been found very stable (less then 1% error). It confirms that it is not necessary to be far from the source to identify the dipole and quadrupole, contrary to the standard solution [4-6].

The second verification concerns the shifting of the inductor versus the center of the decomposition. This implies a more complex field (i.e. higher orders in the decomposition) [10]. Only dipole identification is concern by this phase. The results of FEM simulation show that an error on the dipole determination occurs. It is attributed to the contribution of B_{5m} (and B_{7m} …) terms in our sensor. However, the error is reasonable, and lower than using the standard antenna, since this latter is sensitive to B_{3m} and B_{5m}.

All these results are illustrated in Fig. 5. It shows the interest of using dedicated sensors, which are more robust than previous ones and than punctual measurements.

V. Conclusion

The spherical harmonic decomposition is an interesting method to synthesize a magnetic field, for EMC interaction studies for instance: the very compact representation is extremely attractive. To identify the components of the decomposition, it seems not convenient to use several punctual measurements. Therefore, we choose to develop dedicated sensors,

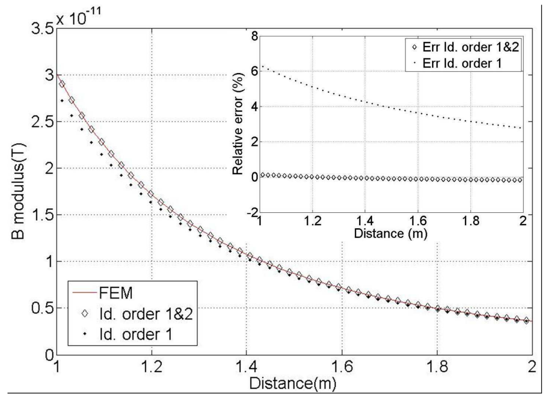

Figure 4. Magnetic field decrease (modulus) vs the distance to the source: comparison between the identified dipole/quadrupole and the actual simulated field

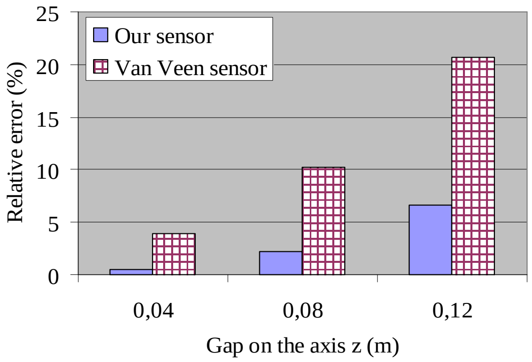

Figure 5. Comparison between Van Veen antenna and our sensor: relative error compared to the actual dipole. The dipole computation is achieved by summing the three components of the dipole: $\left\|\overrightarrow{M}\right\| = \sqrt{A_{1-1}^{\ 2} + A_{10}^{\ 2} + A_{11}^{\ 2}}$

sensitive to specific harmonics only. These coils have been designed, with special shapes, until the second order of the decomposition. The validation of all sensors has been carried out using FE software. It has shown a better robustness than previous standard antenna.

In Future work, propagation effects in the decomposition may be added, and its influence on sensor design studied.

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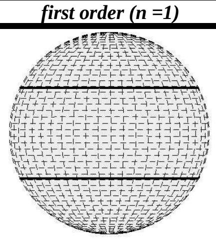
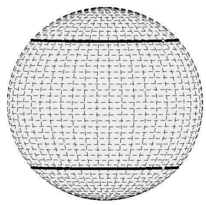
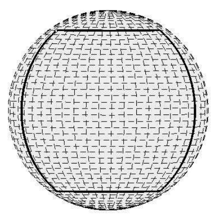
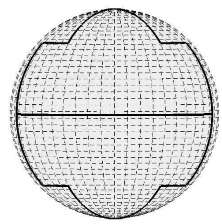
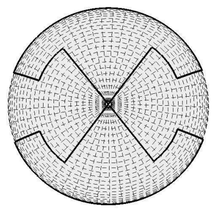
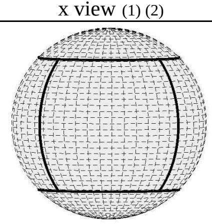
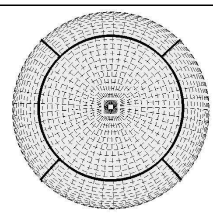
VI. Appendix

Shape of the sensors			
	first order (n =1)	***second order (n = 2)***	
m = 0			
m = +/-1	 (1) (2)	 x view (1) (2)	 z view
m = +/-2		 x view (1) (2)	 z view

1 Same shape in the opposite side,

2 for m < 0, sensors are rotated by $\varphi = \dfrac{\pi}{2|m|}$