New Measurement System of Magnetic Near-field with Multipolar Expansion Approach

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In EMC behavior of power electronic converters, it is important to predict near-field coupling between the complex components (e.g. in EMC filter). By using the components of near-field multipolar expansion of electromagnetic sources, the close magnetic coupling between two elements is determined from their equivalent model. In this paper a new measurement system, based on spherical harmonics and spatial filtering is proposed and studied. The sensor is a single coil moving along one axis, coupled with a rotatable mount for the measured source with two axes of rotation θ and φ. This simple system, which can be easily automated, allows building good accuracy models for complex sources. The impact of the uncertainties in position and orientation of the source and sensor are studied in order to determine the higher degree of the multipolar expansion that can be characterized. Taken into account these uncertainties and the expected precision of the reconstructed source, strategies of measurement minimizing the number of measurements are compared.

Index Terms— **Electromagnetic Compatibility, mutual coupling, power electronic.**

I. Introduction

CHARACTERIZATION of electromagnetic interference (EMI) generated within the power electronic systems is an important activity in electromagnetic compatibility (EMC). However, EMC behaviors are currently treated after the development of a prototype; this leads to additional costs and significant delays in manufacturing in case of malfunctioning due to EMI. In order to study the problems of EMC directly at the design phase, EMC predictive modeling methods must be developed.

One of the important things to predict is the near magnetic field coupling. The method developed in our laboratory is based on the multipolar expansion in spherical harmonics of the radiation near field around the element. This element is represented by an equivalent punctual source composed of components of a multipolar expansion, which allows calculating the near-field coupling with other radiating elements [1]. In a previous work, a measurement method was developed to determine the zero-order components of the first four degrees of the multipolar expansion (Q_{i0}, i=1,4) [2]. In [3], a complete coil set (composed of both zero- and non-zero-order components) for multipolar expansion identification was presented, but the study stopped at second degree and no experimental validation has been done for the non-zero-order components. To overcome this difficulty and simplify the sensors' shapes, an approach of sensor rotation was presented in [3][4] and realized in [5]. The idea is to generate the non-zero-order components from the rotational and linear combination of the zero-order components of the same degree. In [1], the design and the signal analysis was thought to be as simple and efficient as possible, but only for the first and second degrees.

The increasing of the precision of the model has a cost on complexity of the measurement system and measurements analysis. A fixed system with a complete set of coils adapted for a sphere of measurement with a fixed radius has some limits. The nearness of coils for the different degrees causes some spatial trouble, the distances between some coils being too small for the design of adapted mecanical supports. So the extension to higher degrees than the fourth is an issue : six new coils may be added for the fifth degree and six others for the sixth degree. Moreover in order to avoid inductive coupling between the measurement coils, each measurement is done with the active coil in short circuit while the others coils are open. This process gives better results than a calculated compensation of the coupling effects as proposed in [6] but is not easy to automate (moreover, [5] shows that the complete measurements over 17 pairs of angles (θ,φ) are needed to get the complete information till 3^d degree.)

In this paper, a new approach is proposed, which allows automating the measurements, increasing the precision of the reconstructed source and taking into account the uncertainties. This new approach is still based on flux measurements, but there is a unique coil moving along one axis, while the source rotates along two angles (θ,φ). A theorical and numerical study of this system is proposed, considering only the zero-order (higher orders will be discussed in the 4-pages paper). An overview of the impact of an error of coil or source position is presented, in a first step on the coefficient of the multipolar expansion, then on the flux measurement and on the model of the reconstructed source. Different strategies for the choice of the number of measurements and corresponding positions of the coil are studied in relation with the question of uncertainties.

II. Multipolar Expansion: Theoretical Recall

The multipolar expansion in spherical harmonics is used for electromagnetic field representation satisfying Maxwell's equations. It allows decomposing any near field into an infinite sum of known standardized terms (dipole, quadrupole, octupole, etc.). For the near field studies (< 1m) in the 20kHz-20MHz range, the quasi-static approximation is suitable.

The multipolar expansion of the magnetic field in a given spherical coordinate (r,θ,φ) for a point outside the exsphere of the real source, is expressed for each frequency as follow:

$$\mathrm{B}(r,\theta,\varphi) = -\mu_0 \nabla \psi(r,\theta,\varphi) = \sum_{n=1}^{+\infty} \sum_{m=-n}^{+n} \mathrm{B}_{nm}(r,\theta,\varphi) \quad (1)$$

$$\text{with } \mathrm{B}_{nm} = -\frac{\mu_0}{4\pi} \cdot Q_{nm} \cdot \nabla \left(\frac{1}{r^{n+1}} \cdot S_{nm}(\theta,\varphi) \right) \quad (2)$$

where r is the distance from the center of the expansion to the point where the field is expressed, Q_{nm} are the coefficients describing the source (they depend on the choice of the center of the expansion) and S_{nm} are the real spherical harmonic functions of n degree and m order.

The magnetic flux of component nm across the coil sensor $n'm'$ can be calculated by the integration over the surface of coil sensor as follows:

$$Flux_{n'm'}^{nm} = \iint_{S_M} C_{n'm'}(\theta,\varphi) \cdot \mathrm{B}_{nm}(r_M,\theta,\varphi) \cdot \mathbf{n} \cdot dS \quad (3)$$

where C_{nm} is the sensor function defined in [4] and $\mathbf{n}$ is the unit outgoing normal of the sphere S_M.

By using (2), the flux in (3) can be written as:

$$Flux_{n'm'}^{nm} = \frac{\mu_0}{4\pi} \cdot \frac{n+1}{r_0^{n+2}} \cdot Q_{nm} \cdot \iint_{S_M} C_{n'm'}(\theta,\varphi) \cdot S_{nm}(\theta,\varphi) \cdot dS \quad (4)$$

We obtain the coefficient Q_{nm} of the expansion by matching the measured flux value with (4).

III. Impact of an Error of Position

A. Impact of a translation on the Qnm

Is it pertinent to evaluate higher degrees of the multipolar expansion of near-field sources, taking into account the experimental errors, in particular the relative source-coil position errors? To address this issue, the case of the translation of a magnetic dipole following the z axis is studied. The impact on the coefficient of the corresponding multipolar expansion is shown in Fig. 1. : the dipolar coefficient is not modified; the translation essentially impacts the first higher coefficient (Q_{20}) with a linear behavior of slope $k_{1,2}$=0.447. The impact is dramatically small for higher orders.

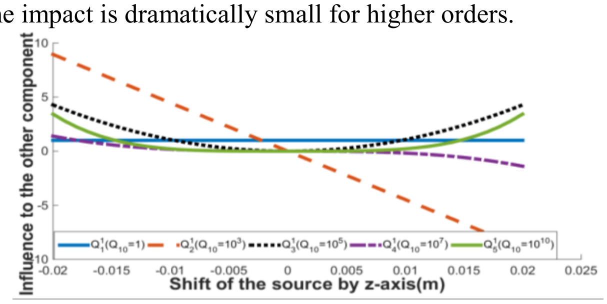

Fig. 1. Influence of a shift from -2 to 2 [cm] of a dipole to the higher orders. Amplitude ratio: 10^3 for Q_{20}, 10^5 for Q_{30}, 10^7 for Q_{40} and 10^{10} for Q_{50}.

Equivalent results were obtained for quadrupoles and octupoles: the translation essentially impacts the first higher coefficient (Q_{30} for the quadrupole, Q_{40} for the octupole,…), with the same linear behavior.

B. Impact of an error of position on flux and rebuilt model

The impact on the reconstructed model of the position uncertainties was evaluated in function of the number of measurements, evenly distributed on the vertical axis. The uncertainties are taken into account with a normal distribution of the sensor position errors (10000 simulations for each case). Table 1. shows the mean relative error µ for each coefficient of the multipolar expansion of a smoothing inductor [2]: Q_{10} = 6.8e-2; Q_{20} = 4.43e-4; Q_{30} = -7.94e-5; Q_{40} = -2.18e-5 as a function of the number of measurements N evenly distributed over a cylinder or over a half cylinder.

TABLE I
Mean relative error µ on rebuilt Q_{n0} coefficients of a smoothing inductor in function of the number of measurement N evenly distributed over a cylinder or over a half cylinder following the z axis.

	Half cylinder				*Full cylinder*			
N	Q_{10}	Q_{20}	Q_{30}	Q_{40}	Q_{10}	Q_{20}	Q_{30}	Q_{40}
4	$1.3e^{-2}$	$8.9e^{-1}$	$6.9e^{-1}$	$1.2e^{-1}$	$3e^{-4}$	$1.3e^{-2}$	$1.5e^{-2}$	$1.2e^{-2}$
12	$2.9e^{-3}$	$2e^{-1}$	$1.7e^{-1}$	$3.4e^{-2}$	$1.9e^{-4}$	$9.2e^{-3}$	$8.9e^{-3}$	$5.9e^{-3}$
20	$2.5e^{-3}$	$1.7e^{-1}$	$1.4e^{-1}$	$2.8e^{-2}$	$1.4e^{-4}$	$7.2e^{-3}$	$7.1e^{-3}$	$4.8e^{-3}$

The magnetic flux is first computed for each component at each equivalent position of the sensor over a sphere (see fig. 2), then the error position of the sensor is added by shift with the Wiener operator [1], the flux over the sensor moving along the cylinder is deduced with a homothety (see fig. 2) on the radius of the sphere which impacts each Flux_{nm} in $1/r^{n+2}$ (eq.4). The coefficients Q_{nm} of the source is then deduced with the least square method. Computing the flux by the following method (instead of a direct computation) reduces the computation time by a factor 13.

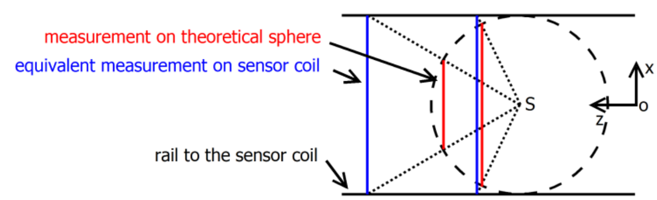

Fig. 2. Transition from sphere to the cylinder.

IV. Conclusion

A new approach and measurement system of near-field source for modeling with multipolar expansion of the coupling between sources was proposed. Extended results on orders, impact of an error of orientation of the source and strategies of distribution of the measurements will be detailed in the extended paper.

V. References

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