



**HAL**  
open science

## Modeling the near-field coupling of EMC filter components

Sanâa Zangui, Kévin Berger, Christian Vollaire, Edith Clavel, Ronan Perrussel, Benjamin Vincent

► **To cite this version:**

Sanâa Zangui, Kévin Berger, Christian Vollaire, Edith Clavel, Ronan Perrussel, et al.. Modeling the near-field coupling of EMC filter components. EMC, Jul 2010, Fort Lauderdale, FL, United States. pp.825 - 830, 10.1109/ISEMC.2010.5711386 . hal-00520119

**HAL Id: hal-00520119**

**<https://hal.science/hal-00520119>**

Submitted on 22 Sep 2010

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# MODELING THE NEAR-FIELD COUPLING OF EMC FILTER COMPONENTS

S. Zangui\*, K. Berger \*, C. Vollaire\*, E. Clavel\*\*, R. Perrussel\*, B. Vincent\*

(\*) : Laboratoire Ampère – UMR CNRS 5005, Ecole Centrale de Lyon, 36 Avenue Guy de Collongue, 69130 Ecully, [sanaa.zangui@ec-lyon.fr](mailto:sanaa.zangui@ec-lyon.fr), [christian.vollaire@ec-lyon.fr](mailto:christian.vollaire@ec-lyon.fr), [benjamin.vincent@ec-lyon.fr](mailto:benjamin.vincent@ec-lyon.fr), [ronan.perrussel@ec-lyon.fr](mailto:ronan.perrussel@ec-lyon.fr)

(\*\*) : Laboratoire G2Elab – UMR CNRS 5269, Site principal campus ENSE3 bat D 961, rue Houille Blanche BP 46, 38402 St Martin d'Hères Cedex, [edith.clavel@g2elab.grenoble-inp.fr](mailto:edith.clavel@g2elab.grenoble-inp.fr)

**Abstract**—EMC filters are increasingly integrated into power applications. To improve the filter performance it is important to model the electromagnetic interference between components to optimize their positions. In this paper, a method is proposed to construct the equivalent model of the filter components. The proposed method proposed is based on the multipolar expansion by representing the radiation emission of generic structures in a spherical reference  $(r, \theta, \varphi)$ . These models of the sources will be used to compute the mutual inductance between the components according to their layout.

## I. INTRODUCTION

EMC filters are designed to improve the electromagnetic compatibility and the immunity level of electric and electronic systems, in particular the aspects concerning power quality and electromagnetic signature. For this reason the behavior of these filters has to be studied. There are two types of parasitic parameters: the self-parasitic of the filter components and the mutual parasitic that reflect the coupling between components. Fig.1 represents the electric model of an EMC filter «  $\Pi$  » consisting of two capacitors  $C_{y1}$  and  $C_{y2}$ , and an inductance  $L_{DM}$ . This model includes the self-parasitic of the filter components and the coupling between components [1]. Due to the significant current values related the filter when compared with the voltage one, this simplified model is assumed.

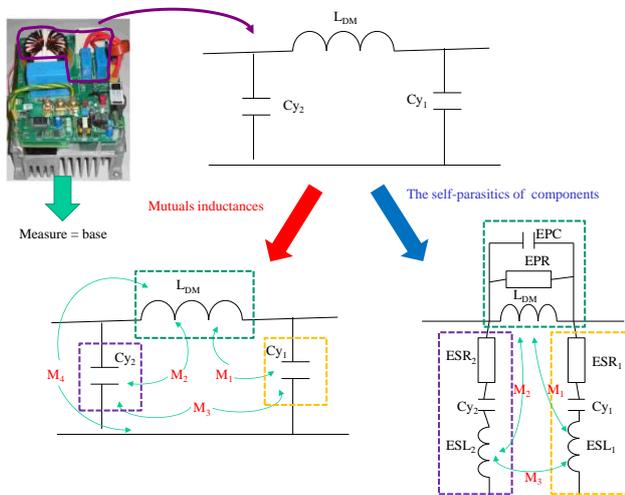


Fig.1 – Filter with parasitic coupling and the self-parasitic.

In Fig.1 the following notations are used:

- ESL, ESR, C: The self-parasitic of the capacitors.
- $L_{DM}$ , EPC, EPR: The self-parasitic of the inductor.
- $M_1$  and  $M_2$ : Coupling between  $L_{DM}$  and the capacitors.
- $M_3$ : Coupling between the capacitors.
- $M_4$ : Coupling between the track and the inductor.

These parasitic parameters affect EMC filter performances. In Fig.2, it is illustrated the influence of the mutual parasitic parameters regarding the performances of the filter. The first resonance (in red) frequency matches the couplings between the filter components (mutual inductances) : there is an improvement between the curve labeled “Base” where the couplings are significant and the curve labeled “Minimized coupling” where the performance of the filter has been improved by optimizing the location of the components to reduce the coupling between filter components. The self-parasitic of components can also impact the performances of the EMC filter. The curve ‘Minimized coupling + ESL cancellation’ is the simulated result of the EMC filter model when we reduce the mutual parasitic and the effect of the equivalent serial inductance (in blue).

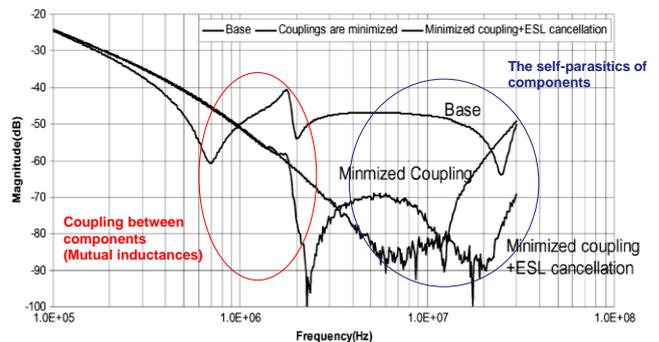


Fig.2 – Effect of parasitic parameters, extract from [2].

This result was obtained from the literature [2]. Thus, in a converter including passive and active components, the fundamental problem is to model the mutual parasitic between these components.

Currently, there is not a suitable methodology that takes into account the near-field coupling between

components when a accurate evaluation of the performances of a filter.

The objective of this work is to propose models that could represent the radiated field of the filter components in a wide range of frequencies. These models will be applied in the determination of the coupling between the filter components by computing the mutual inductance depending on certain parameters, such as the distance between components.

As the distance between components is much smaller than the wavelength of the frequencies of power electronic applications, usually ( $f < 100\text{MHz}$ ), a quasi static approach can be considered. It is the case of a magnetic source, in which the capacitive effects are negligible.

The method proposed to determine the equivalent model of the component radiated field is based on the multipolar expansion. It can be used to represent the radiation of generic structures (coils, capacities, tracks...). It will be considered in a spherical reference  $(r, \theta, \varphi)$ .

This method will be used to compute the coupling between discrete components (capacitors, resistances and inductances) of filters. To simulate the whole structure, the connectors are also taken into account. The PEEC method is used to determine the inductive and resistive effects (R, L, M). On the other hand, for parasitic capacitors, MoM (Moments method) and the fast multipolar method FMM [3] are used. For the connector meshing, the equivalent sources corresponding to discrete components can be integrated. This should simplify the model and gain memory capacity.

## II. MULTIPOLAR EXPANSION

### A. Definition

The multipolar expansion can be used to represent the electromagnetic fields in 3D. This expansion is correct only for the example in Fig.3, when the field is computed at a distance  $r \geq r_2$ . It can also be used in the case of an electric source.

The multipolar expansion of the electric and magnetic fields, is deduced from the solution of the magnetic vector potential  $A_r$  and the electric vector potential  $F_r$  given by [5] :

$$F_r(r, \theta, \varphi) = \sum_{n=1}^{\infty} \sum_{m=-n}^n Q_{nm}^{(cf)} \hat{B}_n^{(cf)}(kr) P_n^m(\cos\theta) e^{jm\varphi}$$

$$A_r(r, \theta, \varphi) = \sum_{n=1}^{\infty} \sum_{m=-n}^n Q_{nm}^{(ca)} \hat{B}_n^{(ca)}(kr) P_n^m(\cos\theta) e^{jm\varphi}$$

The notations (cf) and (ca) determine the type of the function  $\hat{B}_n(kr)$ . For example, for a progressive wave propagating along  $(+r)$  for:

$c = 4$ , and  $\hat{B}_n(kr) = \hat{H}_n^{(2)}(kr)$ , it will correspond to the spherical Hankel functions [5].

If these functions are chosen, the expressions of the electric field  $\mathbf{E}$  and the magnetic field  $\mathbf{H}$  can be represented by:

$$\mathbf{E}(r, \theta, \varphi) = \sum_{n=1}^{\infty} \sum_{m=-n}^n Q_{nm}^{(4)} F_{1nm}^{(4)}(r, \theta, \varphi)$$

$$\mathbf{H}(r, \theta, \varphi) = \frac{j}{\eta} \sum_{n=1}^{\infty} \sum_{m=-n}^n Q_{nm}^{(4)} F_{2nm}^{(4)}(r, \theta, \varphi)$$

with  $\eta = \sqrt{\frac{\mu}{\epsilon}}$  the intrinsic impedance of the considered environment.

The coefficients  $Q_{nm}^{(4)}$  describe the intensity of the transverse-electric (TE) components of the radiated field. This coefficient is the parameter to be identified in order to characterize the equivalent model of the radiated field component.

$F_{1nm}^{(4)}$  and  $F_{2nm}^{(4)}$  are the vector's spherical harmonics which are a solution of Maxwell's equations in free space, excluding the sphere that involves the sources. To compute the vector spherical harmonics, the solution of the scalar Helmholtz equation is used :

$$F_{1nm}^{(4)} = \vec{\nabla} \times (\Psi_{nm}^{(4)} r) \quad F_{2nm}^{(4)} = \frac{1}{k} \vec{\nabla} \times F_{1nm}^{(4)}$$

Where the solution of the Helmholtz equation is expressed as follows

$$\Psi_{nm}^{(4)}(r, \theta, \varphi) = \frac{j}{\sqrt{n(n+1)}} Q_{snm}^{(4)} b_n^{(4)}(kr) Y_{nm}(\theta, \varphi)$$

Where  $Y_{nm}$  are the normalized spherical harmonics

$$Y_{nm}(\theta, \varphi) = \sqrt{\frac{2n+1(n-m)!}{4\pi(n+m)!}} P_n^m(\cos\theta) e^{jm\varphi}$$

$n$ : degree,

$m$ : azimuthal order,

$k$ : the phase constant,

$r$ : distance from the center of the coordinate system,

$b_n$ : The Bessel functions,

$P_n^m$ : The Legendre associated functions

### B. Application

It should be mentioned that, in order to represent the component radiated field in spherical harmonics, it is necessary to compute the coefficients of the decomposition  $Q_{nm}$ . These coefficients are functions of  $\mathbf{H}(r, \theta, \varphi)$ , and can be obtained by applying [5]:

$$\mathbf{H} = \frac{j}{\eta} \sum_{n=1}^{\infty} \sum_{m=-n}^n \frac{(2n-1)!!}{(kr)^{n+2}} N_n^m e^{jm\varphi} Q_{nm}^{(4)} \begin{cases} n(n+1)P_n^m(\cos\theta)\hat{a}_r \\ -n\frac{dP_n^m(\cos\theta)}{d\theta}\hat{a}_\theta \\ -n\frac{jmP_n^m(\cos\theta)}{\sin\theta}\hat{a}_\varphi \end{cases}$$

with

$$N_n^m = j \sqrt{\frac{2n+1}{4\pi} \frac{(n-m)!}{\sqrt{n(n+1)}(n+m)!}}$$

Depending on the complexity of the object to model, we can calculate the radiated  $\mathbf{H}$ -field by using a 3D model or by performing experimental measurements [4].

### III. COMPUTING THE MUTUAL INDUCTANCE

#### A. Mutual inductance

Using the equivalent models of components radiated field source model, we can determine the coupling between two equivalent source models 1 and 2 through the computation of the mutual inductance. The Fig.3 illustrates the configurations regarding the representation of two radiating sources.

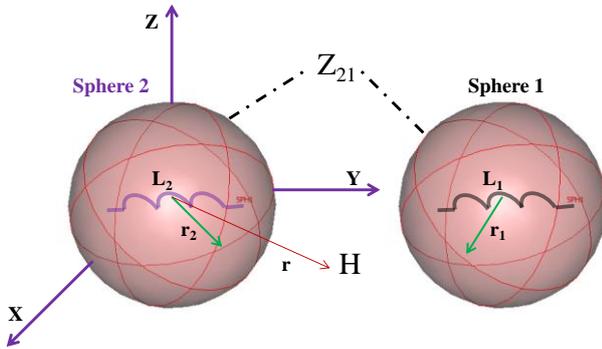


Fig.3 – Representation of two radiating sources.

The computation of the mutual impedance between source 1 and source 2, can be expressed in terms of the electrical field  $\mathbf{E}$  and magnetic field  $\mathbf{H}$  for each source, by [5]:

$$Z_{12} = -\frac{1}{i_1 i_2} \iint_{\Sigma_1} (\mathbf{E}_1 \times \mathbf{H}_2 - \mathbf{E}_2 \times \mathbf{H}_1)$$

When the spheres which contain each of the sources don't intersect, the mutual impedance can be expressed according to the coefficients of the multipolar expansion [5]:

$$Z_{12} = \frac{1}{i_1 i_2} \frac{1}{k^2} \sqrt{\frac{\epsilon_0}{\mu_0}} \sum_{n=1}^{N_{max}} \sum_{m=-n}^n (-1)^m ({}_1Q_{n,-m}^{(4)} * {}_2Q_{nm}^{(4)})$$

The expression of the mutual inductance is:

$$M_{12} = \frac{1}{j\omega i_1 i_2} \frac{1}{k^2} \sqrt{\frac{\epsilon_0}{\mu_0}} \sum_{n=1}^{N_{max}} \sum_{m=-n}^n (-1)^m ({}_1Q_{n,-m}^{(4)} * {}_2Q_{nm}^{(4)})$$

$i_1$  and  $i_2$  are respectively the current circulate in the source 1 and 2,  $k$  are phase constant.

The coefficients associated to the magnetic transverse modes of the multipolar expansion of sources 1 and 2 must be expressed in the same reference. Thus, a translation is required, for example, the coefficients of the source 2 can be expressed in the reference of the source 1.

#### B. Translation and rotation of the coefficients $Q_{nm}$

The rotation of the coefficients  $Q_{nm}$  is obtained by applying the Euler angle reference formulas. It should be mentioned that only two angles are necessary because of the spherical symmetry. The details of the methodology for determining the rotation matrices for complex or real coefficients  $Q_{nm}$  are presented in [6]-[8].

The translation is based on the « Addition Theorem for Vector Spherical Harmonics » [7].

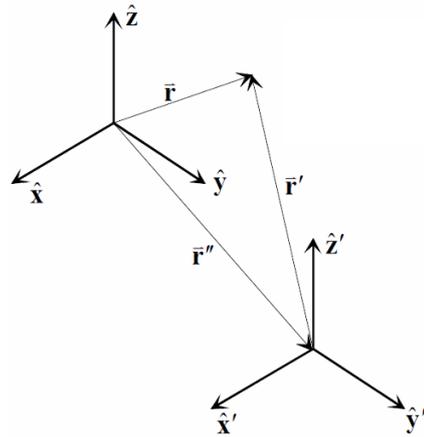


Fig.4 – Translation of a spherical basis

The addition theorem links the harmonics evaluated on  $r$  to those evaluated on  $r'$ , where  $r$  is measured from the origin of the second spherical basis, whose axes' are parallel to the first. The origin of the second spherical basis is located in the first by  $r''$ . These 3 vectors are connected by the relation  $r = r' + r''$ .

The expression of the translate coefficients  $Q_{nm}$  are:

$$Q_{nm} = \sum_{n=1}^{\infty} \sum_{m=-n}^n Q_{1mn} A_{n',m',n,m}$$

The coefficient  $A_{n',m',n,m}$  involve computing of the Wigner 3j symbol according to quantum mechanics [8].

### IV. VALIDATION

To validate the method of computing the mutual inductance between two equivalent radiated field of the

components, the analytical result was compared to the numerical result computed in Flux3D® [9]. For this proposal, two similar loops configuration are considered,  $C_1$  and  $C_2$ . This is a simple case, which, objective is to validate this method in the case of a filter, for two coils.

#### A. First case

We consider two loops,  $C_1$  and  $C_2$  with a radius “Rspire” of 10 cm separated by  $r$ , both located on the Oz-axis as shown in the Fig.5. The minimum sphere of validity is the sphere which surface includes the source. In our case the radius of the sphere was assumed equal to the radius loop.

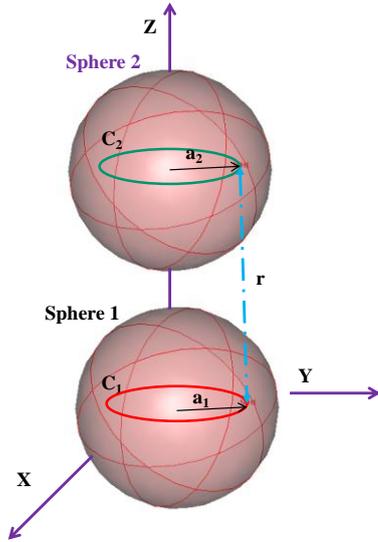


Fig.5 – Two similar coils placed on the z axis

The method of computing the mutual inductance in flux3D® is based on the computation of the flux through the surface of one of the two loops.

In this case, we compute the mutual inductance between the loops according to the distance  $r$  using the method of spherical harmonics for  $n=3$  and  $n=5$ , and on the simulation of the flux through the surface of one of the two loops. The result is compared with those computed by Flux3D. The comparison between the results is shown in the Fig.6.

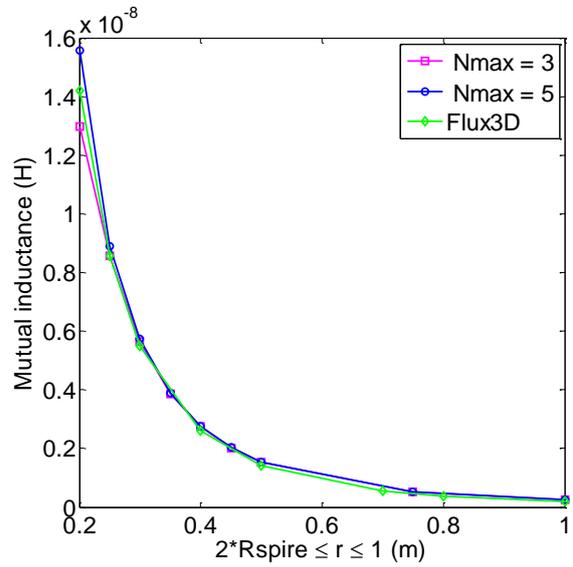


Fig.6 – The comparison between spherical harmonics mutual inductance result and Flux3D® up to the near-field distance limit at 200MHz (1m)

Using the equivalent models of each loop to compute the mutual inductance, there must be no intersection between the spheres that include the source for which of the mutual inductance that will be computed, which has a minimum distance of  $(R_{\text{coil1}} + R_{\text{coil2}}) = 0.2\text{m}$  between their centers.

As shown in Fig.6, the results between the method using a truncated multipolar expansion and the numerical method in Flux3D® are comparable.

To compute the mutual inductance for a small distance between the two loops, the number of terms required to describe the complexity of the source increases. For that reason the error at distance of  $r=0.2\text{m}$  is greater for  $n=3$  than  $n=5$ , as show in Fig.7.

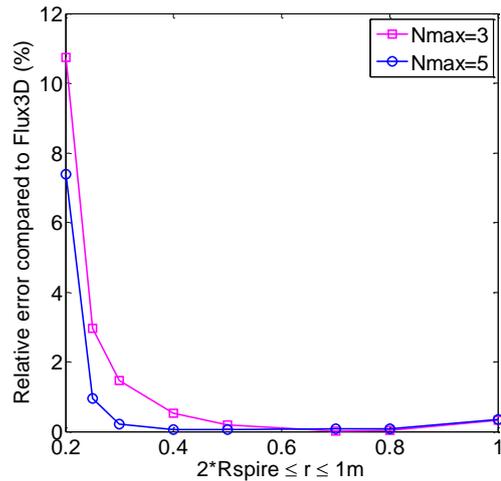


Fig.7 – The relative error compared to Flux3D®

#### B. Second case

In the second case the numerical method is validated when the theorem to rotate the coefficients  $Q_{2nm}$  of the

loop  $C_2$  is applied. A rotation of  $45^\circ$  around the  $y$  axis corresponds to the 2<sup>nd</sup> Euler angle as shown in Fig.8

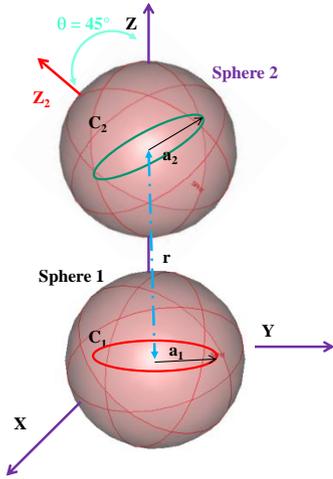


Fig.8 – Two similar coils in  $oz$  axis where the coil  $C_2$  is rotate of  $45^\circ$  than the the coil  $C_1$ .

To compute the mutual inductance between the two loops, in the spherical basis of the loop  $C_1$ , it will be necessary to rotate the coefficients  $Q_{2nm}$  of the loop  $C_2$  before translating them to the spherical basis of loop  $C_1$ . The comparison results of the spherical harmonics method and Flux3D® are represented in Fig.9.

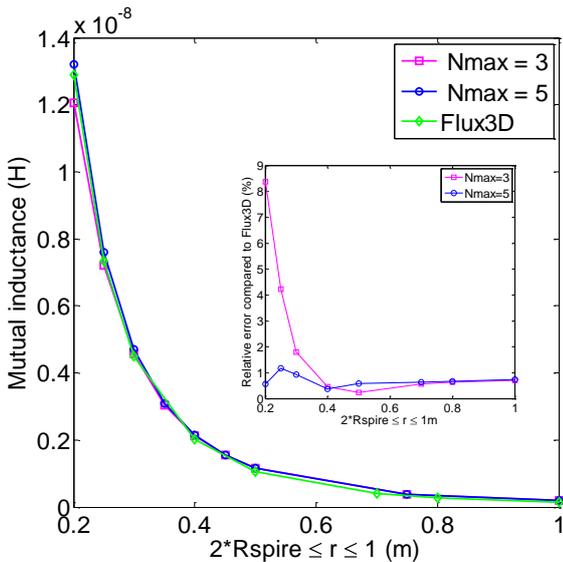


Fig.9 – The comparison between numerical and spherical harmonics results of mutual inductance

The results of the mutual inductance between the two coils are identical to the previous case, at  $r = 0.2m$ , and the error is greater for  $n=3$  than  $n=5$ .

C. Third case

This case is different than the two previous cases because the two coils are not situated on the same axis as shown in Fig.10.

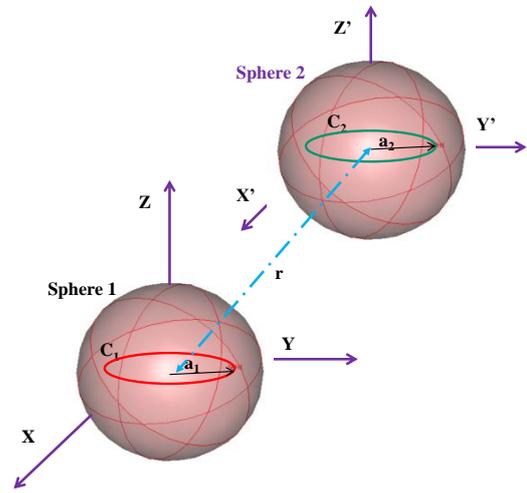


Fig.10 –Two coils which are not situated on the same axis

As in the previous cases, the results for computation mutual inductance are comparable between the method using a multipolar expansion and the numerical result from Flux3D®.

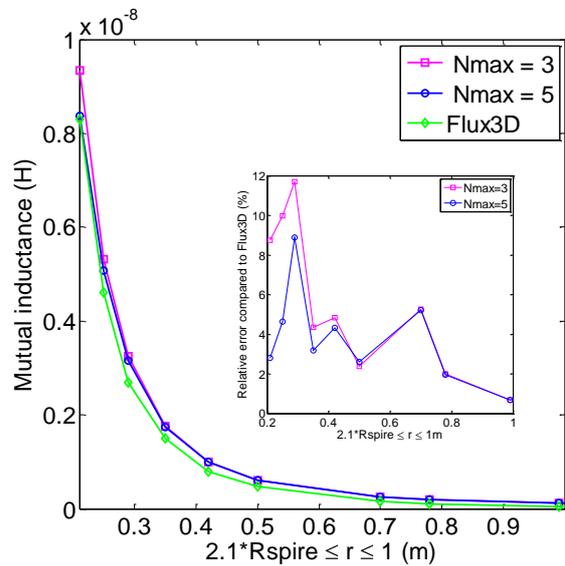


Fig.11 – Comparison of the mutual inductance computing between two coils according to the distance  $r$

V. CONCLUSION

This method allows us to create, at first, the equivalent sources which represent the component radiated field using the multipolar expansion. The equivalent sources will then be used to compute the coupling between them, which was represented by a mutual inductance depending on the distance that separates them.

Although some simple configuration was used to validate the proposed methodology, complex structures should be evaluated in the near future. Other multipolar expansion like the elliptical one can be more suitable for modeling components such as tracks or cables. For example, in the case of the coupling between a track and a component, the spherical harmonic of the equivalent

models of components radiated field is not very well adapted.

The method proposed could be coupled with the PEEC method dedicated to the extraction of equivalent circuit of power electronics devices (R-L-M-C) to simulate the full model of an EMC filter. This will allow considerable gain in memory space concerning the numerical simulations.

Another perspective for this work is to use the method presented in [4] to determine the components of the spherical harmonics by measuring the induced flux through coils placed around the system.

The use of experimental results based on the flux measuring in large coils placed around the system. It allows a “spatial integration” to reduce the effect of the sensor position errors, unlike to the punctual measurement method where the sensor of magnetic field moves around the object to measure the field at many points [4].

The aim is to provide component libraries including equivalent coupling model elements. These will be used to validate and to update our models.

#### REFERENCES

- [1] S.Wang, F.C.Lee and W.G.Odendaal, “*Controlling the parasitic parameters to improve EMI filter performance*”, 2004 IEEE, National science foundation under Award Number EEC-9731677.
- [2] S.Wang, F.C.Lee and W.G.Odendaal, “*Cancellation of capacitor parasitic parameters for noise reduction application*”, IEEE Transactions on power electronics, Vol.21, No.4, July 2006.
- [3] V.Ardon, O.Chadebec, E. Clavel, J-M. Guichon, E. Vialardi V. “*EMC Modeling of an Industrial Variable Speed Drive with an Adapted PEEC Method*”, COMPUMAG, Florianopolis, Brazil, 22-26 Nov 2009.
- [4] B. Vincent, O. Chadebec, J.-L. Schanen, K. Berger, « *Loop antennas for Near Field Multipolar Expansion Identification: First experimental Validations* », to be published in ICONIC 2009 – Special Issue of IEEE Transactions on Instrumentation and Measurement.
- [5] Billy C.Brock « *Using vector spherical harmonics to compute antenna mutual impedance from measured or computed fields* », SANDIA Report, April 2001.
- [6] Miguel A.Blanco, M.Florez and M.bermejo, « *Evaluation of the rotation matrices in the basis of the real spherical harmonics* » , Journal of Molecular Structure : Theochem, Vol.419, Issues 1-3, 8 december 1997, pp. 19-27.
- [7] Advanced Engineering Electromagnetics. Constantine A. Balanis. John Wiley & Sons, 1989, Chapter 10 , pp. 550-552.
- [8] Clebsch-Gordan (C.-G.) Coefficients and '3j' Symbols. A. Messiah, Appendix C.I in Quantum Mechanics, Vol. 2. Amsterdam, Netherlands: North-Holland, pp. 1054-1060, 1962.
- [9] [www.cedrat.com](http://www.cedrat.com)