IDENTIFICATION OF EQUIVALENT SOURCE SYSTEM FOR ELECTROMAGNETIC FIELD POLLUTION EVALUATION

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INTRODUCTION

In the design of extremely low frequency magnetic field shielding, the knowledge of the source data, like current values and space locations are required. Frequently these information are not available and only source types are known and their positions can be roughly predicted. The uncertainty on the source system geometry can be due to: inaccessibility of the source region, for instance because of different ownership or to a fuzzy definition of the geometric position of wiring, for instance when a bunch of wires is placed in a duct. In order to mathematically model the magnetic field created by actual sources, a reconstruction of an Equivalent Source System (ESS) has to be devised.

This problem has already been treated in the literature [1,2,3]. All proposed techniques are based on the subdivision of the space in two parts: the field region and the source region, which is the region containing all the sources (power lines, transformers, panels, etc.). Moreover, the proposed procedures suggest how to evaluate an ESS which is able to generate in the field region the same field distribution produced by the actual sources. The above suggestions have been collected into a new procedure which performs the composition of magnetic fields having cylindrical and spherical like configurations which are suitable to represent respectively multiconductor power lines and transformers or panels. Starting from a qualitative knowledge of the source dispositions and types, the proposed procedure is able to compute the main parameters of equivalent sources which minimize a stated difference (norm) between actual and reconstructed field. The computations are based on suitable solutions of inverse problems. The case of a substation is used as a test case for the proposed approach.

ESS IDENTIFICATION STATEMENT

The starting point of the ESS evaluation is a set of field measurements and, for a good estimation, a rough knowledge of the location, orientation and main size of the sources. In fact, two main source structures can be defined: space limited sources, like transformers, panels and linearly distributed sources like cables and busbars. The inverse problem of defining the ESS for a given set of measurements is defined by the use of different nested modules:

- Magnetic Field Evaluation (MFE) module: this module is responsible of the computation of the magnetic field created by a ESS of linear and loop wires: this result is readily evaluated by the integral of the Biot-Savart formulas when position are defined for each equivalent source;

- Inverse Current Problem (ICP) module: the intermediate level procedure is made by a least square inverse routine which, for a given geometrical distribution of the equivalent source wire, computes the optimal current values through them which minimize the error between the measured and computed field. The least square approximation is based on the Singular Value Decomposition (SVD) of the coefficient matrices computed by the MFE module;

- Source Position Optimization (SPO) module: the geometrical positions of the wires, which are the design variables of the optimization problem, are changed by a stochastic optimization routine which drives them in order to minimize the error on field reconstruction. An Artificial Immune System algorithm has been chosen to solve the source position problem.. This class of stochastic algorithms are focused on the maximal exploration of the design variable space and has shown very good performances on multimodal optimization problems like the one here faced. In order to speed-up the overall definition of conductor positions, a second stage optimization by a deterministic Direct Search based procedure [6] has been used to refine the results.

The proposed procedure has been applied to analyse magnetic fields characterised by complex spatial distributions inside environments were the most significant sources are represented by power lines and transformers. The first kind of source has a predominant cylindrical distribution of the magnetic field which can be subdivided according to a succession of straight lines while in the second case a spherical magnetic field distribution is expected . In the present paper the authors focus their study on the identification of such mixed magnetic fields and the proposed procedure is tested on a typical MV/LV substation layout.

METODOLOGY

Magnetic Field Evaluation (MFE) module

The magnetic fields generated by substations are mainly constituted by cylindrical and spherical components. The first ones are due to power lines, in particular the main contribution is due to the LV output lines, while the second ones are produced by transformers or panels. The ESS has to be constituted by sources able to generate cylindrical and a spherical magnetic field distributions. The most elementary sources are represented by finite linear conductors and loops.

Cylindrical ESS. Usually, when a bunch cable is present, the number of conductors and their mutual locations are unknown and only a rough knowledge of the main orientation of the bunch is available. In the case of a rectilinear orientation of the bunch, each conductor can be considered parallel to the others (Fig. 1a) and its trace, in a plane perpendicular to its axis, is confined inside a rectangular region (Fig. 1b).

As exhaustively analyzed in [7], the magnetic field produced by this kind of sources presents a prevalent cylindrical space distribution. A reasonable ESS is represented by a set of conductors, directed along the main direction and placed inside the same volume of the actual bunch. The positions and currents of the ESS conductors have to be evaluated, while the number of conductors is assumed as a parameter. By

increasing the number of conductors it is possible to improve the identification accuracy but, on the other hand, the computational time increases because of the higher number of degrees of freedom. Anyway, it has been observed that an unbalanced three phase line (3 parallel conductors) is a good compromise between field reconstruction accuracy and computational simplicity.

When the cylindrical source must be subdivided into different successive straight lines it is avoided to ensure any connection of the equivalent electric lines which represent each part. This choose is based also on the strong non uniformity of fields which makes difficult any measure.
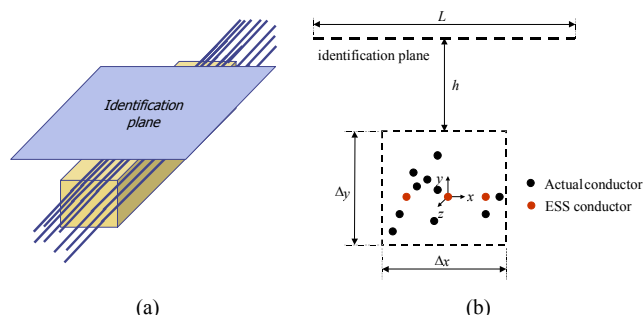

(a)   (b)

Fig. 1 Schematisation of a bunch cable and the corresponding ESS

Spherical ESS. As stated before, transformers and panels generate a magnetic field with a prevalent spherical component distribution. The adopted ESS are in this case a set of loops where the elemental source is constituted by a cluster made of three loops respectively placed on the three coordinate planes (see Fig. 2a). This configuration is related to the first order spherical multipole expansion, as shown in [8].

These sets of clusters are then placed in space on the boundary of a box including actual sources: in Fig. 2b is reported an example of cluster distribution where on the edge along *y* and *z* axis are placed three clusters while on the edge along the *x* axis two clusters are enough.

In order to speed up the evaluation time of the magnetic flux density, produced by the ESS, a closed analytical form must be adopted for both kind of sources. The expression for the finite length straight conductor is reported in [7], while the equations for the spherical sources can be found in [9].
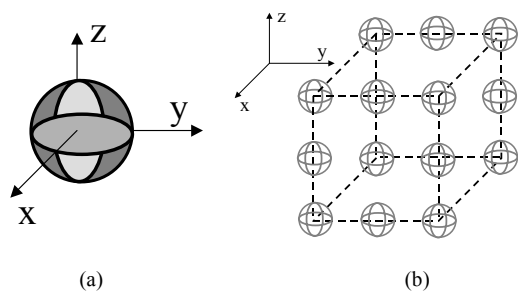

(a)   (b)

Fig. 2 (a): Elemental ESS for spherical field (b). and space location adopted in the identification processes

Inverse Current Problem (ICP) module

When the positions of the sources are set, the evaluation of the current values can be performed by minimizing the error between the measured field and the reconstructed one. This error can be expressed by means of the Euclidean norm:

$$\min\left\|\mathbf{A}\,\mathbf{I} - \mathbf{B}_{act}\right\|_2^2 \qquad (1)$$

where $\mathbf{A}$ is the N_f x N_s coefficient matrix (N_f: number of field points, N_s number of sources and $N_f \geq N_s$) evaluated by the MFE module. It can be shown [10] that the least square problem of Eq. (1) can be solved in terms of singular values of matrix $\mathbf{A}$. This approach has the advantage of regularizing the problem and gives a stable solution also when the sets of equations are numerically very close to be singular.

Given the matrix $\mathbf{A}$, there exist a N_f x N_f orthogonal matrix $\mathbf{U}$, a N_s x N_s orthogonal matrix $\mathbf{V}$ and a N_f x N_s block diagonal matrix $\mathbf{S}$ such that

$$\mathbf{A} = \mathbf{USV}^T = \mathbf{U}\begin{bmatrix}\mathbf{\Sigma} & 0 \\ 0 & 0\end{bmatrix}\mathbf{V}^T \qquad (2)$$

where

$$\mathbf{\Sigma} = diag\left(\sigma_1, \sigma_2, ..., \sigma_{N_s}\right) \qquad (3)$$

and σ_i are the singular values of $\mathbf{A}$.

By defining the Moore-Penrose generalized inverse $\mathbf{A}^\dagger$ of $\mathbf{A}$,

$$\mathbf{A}^\dagger = \mathbf{V\Sigma}^{-1}\mathbf{U}^T \qquad (4)$$

the minimal norm solution for the current vector $\mathbf{I}$ is given by

$$\mathbf{I} = \mathbf{A}^\dagger \mathbf{B}_{act} \qquad (5)$$

Source Position Optimization (SPO) module

Among different stochastic optimization algorithms which have been proposed in the last ten years, Artificial Immune Systems (AIS) have shown a considerable efficiency in dealing with ill-conditioned and multi-modal objective functions.

AIS are based on a natural mechanism intended to defend living bodies against the intrusion of bacteria and viruses. Immune System has to deal with ever different enemies and so it must be flexible and multi-focused [4-5]. Leaving the details to specialized literature, it can be said that the main features of AIS are: the search for different local optima of the objective function and an accurate exploration of the parameter space. These features are mutated by the need of the living body which, using limited resources (Antibodies, Abs), must defend itself from external assaults always different (Antigens, Ags) and a-priori unknown.

This process can be implemented and used for optimization purposes. In AIS, Ags are the optimal points of a function, while Abs are the test configurations, often called *cells*. The optimization search is carried out by modifying Abs in order to have a better affinity, that is a greater value of objective functions if a maximum is looked for, to the Ags.

In the outer cycle the *suppression* operator is applied to the population, in fact if resources are limited it is crucial, to enhance diversity, to remove redundancies. The Euclidean distance between memory cells is measured; all but the highest fitness cells whose distances are less than a threshold are suppressed. The suppressed cells are then replaced with new randomly generated cells. In order to maintain the

diversity of solutions and to obtain a good exploration of the space of the parameters, at each iteration a minimum number of new cells is guaranteed.
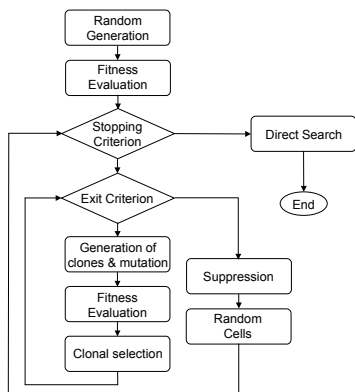

Fig. 3: Flowchart of the Artificial Immune Systems algorithm.

In other words, the inner loop determines the local exploration of a promising zone, while the outer lets the process explore not yet investigated zones. Both loops end if the average fitness of the memory cells does not improve between two iterations or if the number of iterations reaches the maximum value.

At the end of the AIS algorithm, a local refinement of the solution is provided by running a Direct Search [6] procedure for each survived memory cell.

In the proposed implementation, the degrees of freedom of the optimization are the positions of the spherical and cylindrical sources. In order to minimize the number of degrees of freedom of the problem a reduced set of optimization variables is adopted. For the cylindrical ESS a three phase unbalanced line is considered. The conductor are placed on the same plane which can rotate around the middle conductor. The geometrical variables of the identification procedure are chosen as the distance a among conductors and the angle α of the plane while the axial location of the middle conductor is considered as a parameter. In Fig. 4 is reported an example of linear ESS constituted by a three phase line directed along z-axis.
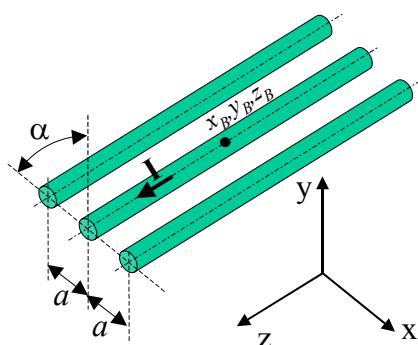

Fig. 4: Cylindrical ESS identification variables

For the spherical ESS, the position of the box barycentre and the number of clusters for each box edge are considered as parameters, while the dimensions of the box: Δx, Δy and Δz are identification variables, as shown in Fig. 5.
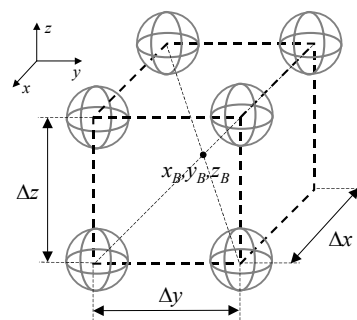

Fig. 5: Spherical ESS identification variables

Measurement setup

It is right and proper to underline some difficulties in the extraction of experimental data. The proposed identification procedure under AC conditions and neglecting harmonic content is based on the knowledge of both amplitude and phase of magnetic field. This kind of information is not usually provided by standard probes. In [8] it is described the measurement setup of environmental magnetic field realized at the University of Southern California, while [11] gives a more detailed analysis of circuits for signal processing.

In this work the identification procedure is applied to the results of a magnetic field 3D FEM simulation in a typical MV/LV substation layout. The values obtained are compatible with those reported in [8] and some measures of field amplitude confirmed the above values.

APPLICATION

The proposed identification procedure has been applied to a practical case represented by a MV/LV substation, with a MV/LV transformer, connections and power lines. The transformer data are reported in Tab. 1.

Three identification planes have been considered. According to the scheme reported in Fig. 6 the three planes are respectively placed beyond, above and at the left hand of the substation (namely P1, P2 and P3). The origin of the coordinate system is placed at the ground level (the substation base) in the middle of the transformer central winding.

The ESS adopted for the field identification is constituted by:
- a set of spherical sources, placed in the volume occupied by the transformer and by the internal LV connection;
- three cylindrical sources, placed along the main three LV bunch cables of the substation.

Fig. 7 shows the final layout of the ESS, at the end of the identification procedure. In Fig. 8 are reported the actual and the reconstructed magnetic flux density distributions on the three planes. The comparison shows that a good identification is obtained on all the three planes. On the contrary, it has been observed that, if only one identification plane is adopted, a very good matching is obtained in such a plane but significant differences on reconstructed field occur in the other ones. This fact implies that all the three planes have to be considered for a good field reconstruction in the all volume around the substation.

The capability of the proposed procedure to reconstruct the field in other planes different form the identification ones has been analysed. Such planes are parallel to the identification

ones at a distance of 1 m coming far from the identification planes. The obtained results are reported in Fig. 9, which shows that also in this case the actual and the reconstructed field are very similar.
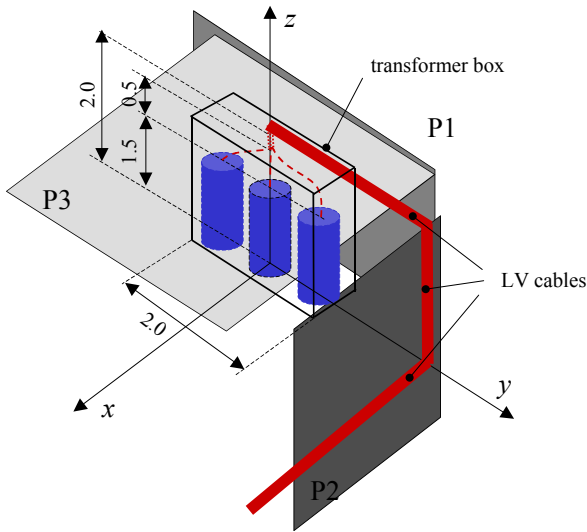

Fig. 6: Outline of the transformer and of the LV power lines with the identification plane configurations (dimensions are in m)
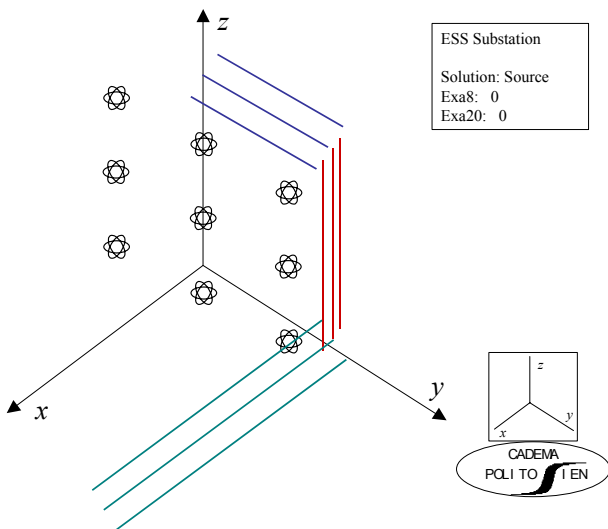

Fig. 7: Outline of the ESS layout at the end of the identification procedure

Table 1: Transformer rated data

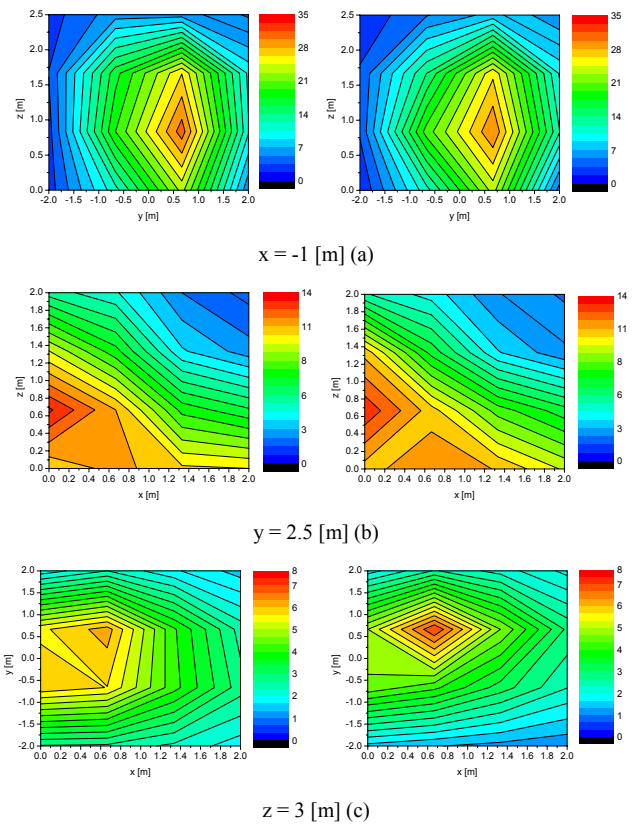| Rated Power	800 kVA
Rated Voltage	
HV	22 +/- 2 X 2,5% kV
LV	400 V
Rated Current	
HV	21 A
LV	1155 A
Insulation	F
Connection	Dyn
Short circuit voltage %	5,86%

x = -1 [m] (a)

y = 2.5 [m] (b)

z = 3 [m] (c)

Fig. 8: Actual and reconstructed magnetic field density distribution (in microtesla) on planes P1 (a), P2 (b) and P3 (c).

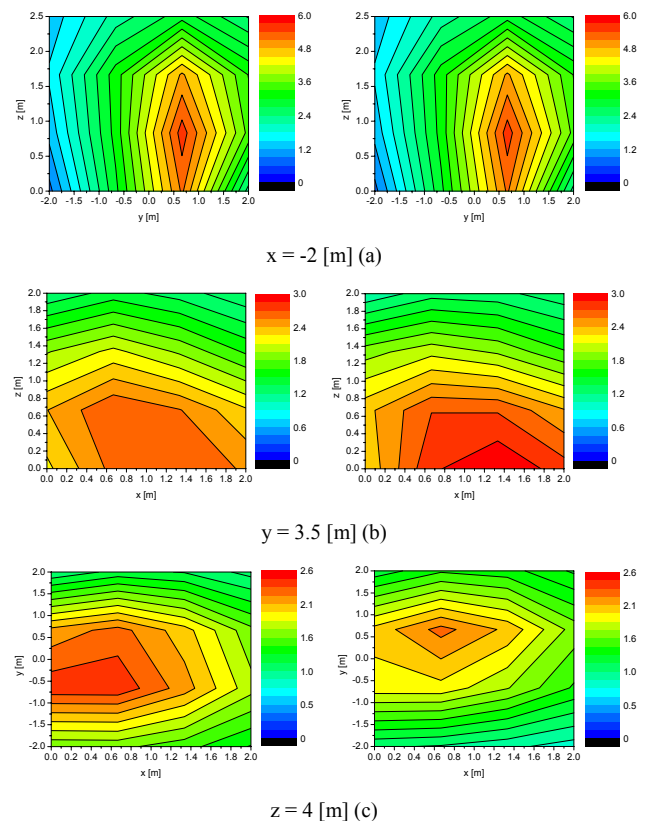x = -2 [m] (a)

y = 3.5 [m] (b)

z = 4 [m] (c)

Fig. 9: Actual and reconstructed magnetic field density distribution (in microtesla) on planes at 1 m far from P1 (a), P2 (b) and P3 (c).

CONCLUSIONS

In this paper an identification procedure suitable for low magnetic field has been presented. The proposed technique employs equivalent source systems based on linear wires and loops. The identification procedure starts from the knowledge of the magnetic field in a certain number of points. The variables are represented by the currents and the geometrical dimensions of the ESS while the number of ESS is assumed as a parameter of the identification process. The procedure has been tested in a test case represented by a MV/LV substation. In a first attempt only one identification plane has been adopted, but the obtained results were unsatisfactory, especially for points far from the identification ones and placed near to the ESS. On the contrary, the choice of space distributed identification points, has in the case of the three orthogonal identification planes, allows a very good magnetic field reconstruction both near and far from identification points.

REFERENCES

[1] R. G. Olsen, C E. Lyon, 1996, Modelling of extremely low frequency magnetic field sources using multipole techniques, *IEEE Trans. on Power Delivery*, Vol. 11, n. 3, pp. 1563–1570.

[2] A. Canova, M. Repetto, M. Tartaglia, 2003, Identification of Industrial Electromagnetic Field Sources, *Kluwer Academic Publishers, Optimization and Inverse Problems in Electromagnetism*, pp. 193-203.

[3] A. Canova, F. Freschi, M. Repetto, M. Tartaglia, 2004, Identification of power frequency industrial magnetic field sources for shielding purposes, *Proceedings of the 39th IEEE IAS Annual Meeting 2004*, pp. 768–773.

[4] L. N. De Castro, J. Timmis, 2002, An Artificial Immune Network for Multimodal Function Optimization, *Proceedings of the 2002 Congress on Evolutionary Computation*, CEC'02, Volume 1 , 12-17 May, pp. 699 – 704.

[5] L. N. De Castro and F. J. Von Zuben, 2002, Learning and optimization using the clonal selection principle, *IEEE Transactions on Evolutionary Computation*, Volume 6 Issue 3, June 2002, pp. 239 – 251.

[6] R. Hooke, T. Jeeves, 1961, Direct Search Solution of Numerical and Statistic Problems, *Journal of the ACM*, Vol. 8, No. 2, April, pp. 212-229.

[7]A. Canova, F. Freschi, M. Repetto, M. Tartaglia, 2005, Description of Power Lines By Equivalent Source System, to be Published on *Selected Papers from The 8th International Workshop on Optimization and Inverse Problems in Electromagnetism*, Special Issue 3, Compel.

[8] C. E. Lyon, 1994, *Modeling of Low Frequency Magnetic Fields Using Multipole Techniques*, M. S. Thesis, Washington State University

[9] C. R. Paul, K. W. Whites, S. A. Nasar, 1998, *Introduction to electromagnetic fields*, 3rd edition, McGraw- Hill, Boston

[10] P. Neittaanmaki, M. Rudnicki, A Savini, 1996, *Inverse problems and optimal design in electricity and magnetism*, Oxford Clarendon Press.

[11] R. Scorretti, 2003, *Caractérisation numérique et expérimental du champ magnétique B. F. généré par des systèmes électrotechniques en vue de la modélisation des courants induits dans le corps humain*, Ph. D. Thesis, Ecole Centrale de Lyon.