Radiation Protection Dosimetry (2004), Vol. 111, No. 4, pp. 343–347
doi:10.1093/rpd/nch051

MAGNETIC FIELDS DISPERSED BY HIGH-VOLTAGE POWER LINES: AN ADVANCED EVALUATION METHOD BASED ON 3-D MODELS OF ELECTRICAL LINES AND THE TERRITORY

D. Andreuccetti* and N. Zoppetti
Italian National Research Council, Institute for Applied Physics 'Nello Carrara', Via Panciatichi 64, Florence, Italy

An advanced numerical evaluation tool is proposed for calculating the magnetic flux density dispersed by high-voltage power lines. When compared to existing software packages based on the application of standardized methods, this tool turned out to be particularly suitable for making accurate evaluations on vast portions of the territory, especially when the contribution of numerous aerial and/or underground lines must be taken into account. The aspects of the tool of greatest interest are (1) the interaction with an electronic archive of power lines, from which all the information necessary for the calculation is obtained; (2) the use of three-dimensional models of both the power lines and the territory crossed by these; (3) the direct interfacing with electronic cartography; and finally (4) the use of a representation procedure for the results that is based on contour maps. The tool had proven to be very useful especially for Environmental Impact Assessment procedures relative to new power lines.

INTRODUCTION

Cases exist in which there is a need for an evaluation of the magnetic flux density (MFD) dispersed by one or more power lines in an assigned portion of the territory, one which is more accurate and detailed than what can be obtained using traditional two-dimensional (2-D) calculation models codified by the CEI 211-4 Italian national technical guideline(1). For example, in environmental impact assessments, situations frequently arise in which, in relatively limited portions of territory, numerous electrical lines with non-parallel courses co-exist: the possibility of crossing-points between them is more often than rare. Furthermore, the search for a relatively high exposure limit, such as that of 3 μT (provided for by a recently published Italian national ministerial decree), requires venturing fairly close to the line, where the catenary progression of the conductors on the vertical plane is not completely negligible. Moreover, should the interest be in finding lower values, of the order of tenths of a microtesla, it is necessary to venture at considerable distances from the line, to where the effects due to the changes in direction of the course in the horizontal plane become significant. Finally, in all cases, an accurate evaluation involving extended regions requires that both the variations in the structural characteristics of the lines in question (due, for instance, to the use of different types of towers) and also the morphology of the territory be taken into account.

These necessities are entirely satisfied by the numerical evaluation tool recently developed at our Institute [in good part within the framework of a specific degree thesis(2)], which is based on the definition of 3-D models for both the field sources (power lines) and a portion of the surrounding territory(3).

The 3-D models of the power lines are built starting from the data contained in an electronic archive which implements a prototype of a land register of the sources of power-frequency electric and magnetic fields. This, in turn, was the result of the development of an activity that originated within a national project in which our research group recently took part in(4).

For the models of the sources and the territory to integrate correctly, maintaining the right spatial relations, both the cartography and the information contained in the archive of sources have to be geo-referenced in the same system of cartographic coordinates. This also guarantees that the results of the calculation will be geo-referenced and will thus be easy to integrate within the same basic cartography.

Management of the models of the sources and the territory integrated in the cartography makes it possible to represent the results of the calculation by means of so-called isolevel maps, i.e. contour maps consisting of a set of 'level' curves (isolevel curves) relative to values of MFD and of the height above ground specified by the user. This method of representation has been found to be particularly versatile, because it synthesises, in graphic form, the results of the calculation, making them understandable even to a non-specialised public.

CALCULATION SESSION

Calculation of the MFD and the tracing of the isolevel curves constitute the so-called calculation session. Every calculation session includes all the operations necessary for tracing a group of isolevel curves along a pre-established electrical line (the main session line), taking into account all the

*Corresponding author: d.andreuccetti@ifac.cnr.it

other lines which contribute significantly to the total field in the vicinity of the main line (secondary session lines). Each isolevel curve is relative to an MFD value specified by the user.

The generic calculation session is characterised by three distinct consecutive steps: in the first of these, the models of the main line and of the possible secondary lines are built by accessing the data in the archive of lines; in the second step, a calculation is made of the MFD and, in particular, the search for the coordinates of the points, with a specified height above ground, in which the values sought after are reached; in the third step, the effective tracing of the isolevel curves is carried out.

Models of the sources

The numerical models of the MFD sources are built at the beginning of the calculation session, and remain in the memory of the processor until the moment in which, upon termination, the application releases all the resources utilised. The necessary data (position, conformation, height and orientation of all the towers of each line and the electrical and mechanical characteristics of the cabling of the relative spans) are acquired from the archive of lines, by being connected in client-server modality (with TCP/IP protocol) to an interface application that is achieved in the C programming language, which, in turn, is connected to the database engine. From the point of view of the database, the use of such an application makes it possible, on the one hand, to isolate from the network the actual archive, increasing the level of protection and reliability, and on the other, to offer to the calculation procedures a standardised interface that is independent of the specific implementation of the archive. Furthermore, the interface application offers several functional capacities for pre-processing the data, which increases the overall efficiency of the system.

The calculation procedures were achieved in the C++ programming language, by adopting an object-oriented programming technique. This approach has made it possible to define the model of the sources in accordance with a very precise hierarchy that permits an integrated management of the data and of the functions that act on them.

The representation of a tract of an aerial power line is based on the definition of an individual geometric model of each of the conductors of each of the spans of the line, in turn consisting in the last analysis of the analytic expression of the catenary curve. As is well known, this curve describes a heavy, homogeneous, non-extendible and perfectly flexible cable that is suspended by its ends and is subject solely to its own weight. The parameters characteristic of each catenary curve are determined depending on the data obtained from the archive, namely, on the coordinates of the fixing points of the conductor and on the parameter that specifies the mechanical strain to which it is subject. By starting from the analytical expression of the catenary, it is possible to determine a subset of its cords which constitutes a simplified representation of it, but one which is sufficiently accurate for the purposes of calculating the MFD.

To model the underground tracts, instead, we resort to a segmented line determined by sampling the surface of the terrain along the course of the line and by subtracting from the elevations of the points obtained the underground depth of the conductors, which is nominally constant. The choice of the vertices of the segmented line is made so as to take into account the changes in direction of the line, on both the horizontal (on the basis of the restraints imposed by the planimetry of the course) and vertical (restraints imposed by the profile of the terrain along the course) planes.

Calculation of MFD

The overall MFD value generated by each line in a generic point Q is calculated by composing vectorially the contributions of all the segments making up the models of the conductors of the line, where for the aerial tracts these segments are catenary cords, while for the underground tracts these are the constitutive elements of the segmented line that represents the conductor. The contribution of each segment is calculated by numerically integrating along it the Biot–Savart law in differential form:

$$\vec{\boldsymbol{B}}_{\text{segm}} = \frac{\mu_0 I}{4\pi} \int_{P1}^{P2} \frac{\mathrm{d}\vec{\boldsymbol{P}} \times (Q - P)}{|Q - P|^3}, \tag{1}$$

where I is the current that flows in the conductor segment, $P1$ and $P2$ are its extremes, P is the generic point and $\mathrm{d}\vec{P}$ is the infinitesimal element on it. Also see Figure 1, where the situation in which the field generated by an aerial line (main line) is calculated by taking into account an underground line located in the immediate vicinity (secondary line).

In the presence of several lines, which contribute significantly to the overall field (as in Figure 1, where two of these are hypothesised), the problem of the combination of the relative contributions is posed. Until now, two different modalities have been considered, called coherent (see Equation 2 below) and incoherent (Equation 3) combination modalities, which correspond, respectively, to the vectorial sum of the various contributions by taking into account the relative phases and to the simple root-sum-square combination of the respective effective values. More in detail, if it is desired to sum the $\vec{\boldsymbol{B}}_i$ contributions of n lines in a given point Q, the two

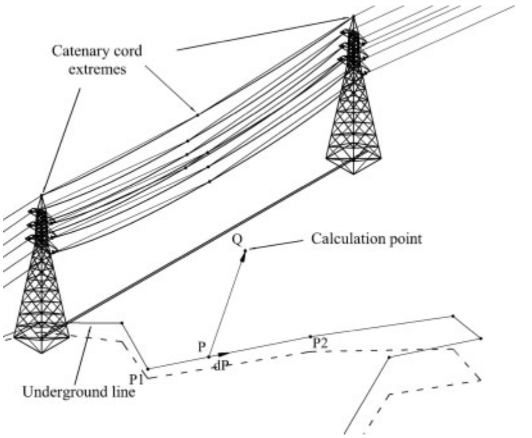

Figure 1. 3-D models of sources. Both aerial and buried power lines are represented with segmented lines. The total magnetic flux density is calculated by summing up the contributions of all the segments.

different modalities are expressed by the relations

$$B_{\text{tot}} = \left|\sum_{i=1}^{n} \vec{B}_i\right|. \tag{2}$$

$$B_{\text{tot}} = \sqrt{\sum_{i=1}^{n} \left|\vec{B}_i\right|^2}. \tag{3}$$

The incoherent combination was introduced because it is more suitable for treating the—anything but rare—cases in which either the phase relations among the currents flowing in distinct and independent power lines are unknown, or the respective intensities are found to be statistically uncorrelated. Although it does not necessarily constitute the worst case, the incoherent sum supplies in these cases a reasonably precautionary estimate.

Results of the calculation

The trend of the isolevel curves is determined, proceeding along the main line and seeking in every section (defined in the following paragraphs) the points in which the sought-after values of MFD are attained. The points relative to the same field value are then connected, as shown in Figure 2, in which is also provided a representation of the sections (see below) in which the particular 'fan-shaped' arrangement is noted in the changes in direction of the course of the line.

Finally, in Figure 3 is reported an example in which is represented the MFD distribution at 1 m above ground in the vicinity of an electrical station on which several lines—both aerial and underground—depend. This representation was obtained by assembling on the same map the results of calculation sessions relative to different main lines (utilising the coherent combination of the contributions from the different lines).

SECTIONING THE TERRAIN

Creation of the 3-D digital terrain model (DTM) and extraction of data from it take place off-line, once and for all, in such a way that the calculation application draws on the information relative to the orography from a text file of appropriate format, independently of the particular type of DTM available. In this study, there is no room for an in-depth examination of the aspects of construction of the DTM starting from the 2-D cartography. It is enough to know that the model itself consists of a file containing triangular elements with levelled vertices, and that it is obtained starting from the levelled points and from the isocline lines of the 2-D cartography, utilising an application that implements the conforming Delaunay triangulation[5].

One of the crucial aspects for the functioning of the calculation application is the so-called 'sectioning the terrain'. A *section of terrain*, or *section* for short, is defined as the set of a finite number of points belonging to the 3-D surface defined by the DTM, identified by moving away with regular steps from the axis of the line, in a transversal direction to it and in both ways (Figure 4). Each section reconstructs the profile of the terrain on the vertical plane to which it belongs, and is memorised in the so-called section file, which contains the data of all the sections obtained along the line of interest. Sections are utilised for determining the elevation of points in which to calculate the field.

The expression 'sectioning the terrain' indicates the process of constructing the sections by proceeding along the axis of a power line. During the sectioning, both the characteristics of the individual sections (such as the width of the section) and the ones which determine how each section is arranged with respect to the others extracted along the same line, are defined. These characteristics are chosen on the basis of both the type of study that it is desired to carry out and the scale of the cartography from which the model of the terrain was obtained, as well as the precision with which the sources are located through their archival data. In particular, the width of the section is linked to the smallest MFD value for which there is interest in tracing the isolevel curve, while the minimum transversal step is conditioned by the resolution permitted by the basic cartography utilised (e.g. this resolution is of the order of 2 m for cartography at a scale of 1:10,000).

Particular care was given to designing a sectioning algorithm which manages the changes in the direction of the line along which we proceed, in order

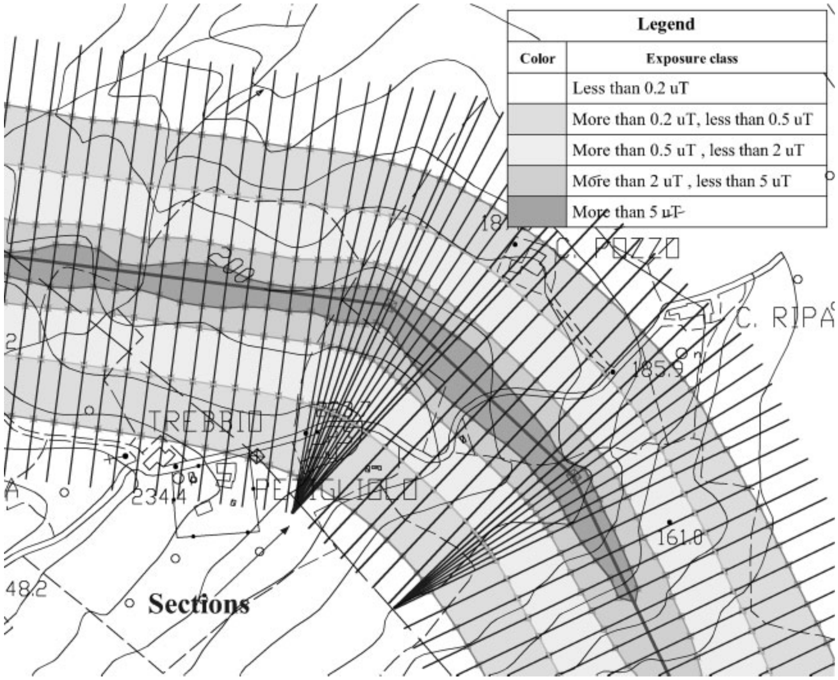

Figure 2. Drawing the isolevel curves relative to a not straight tract of a power line. Note the 'fan-shaped' arrangement used to avoid overlapping of the different sections.

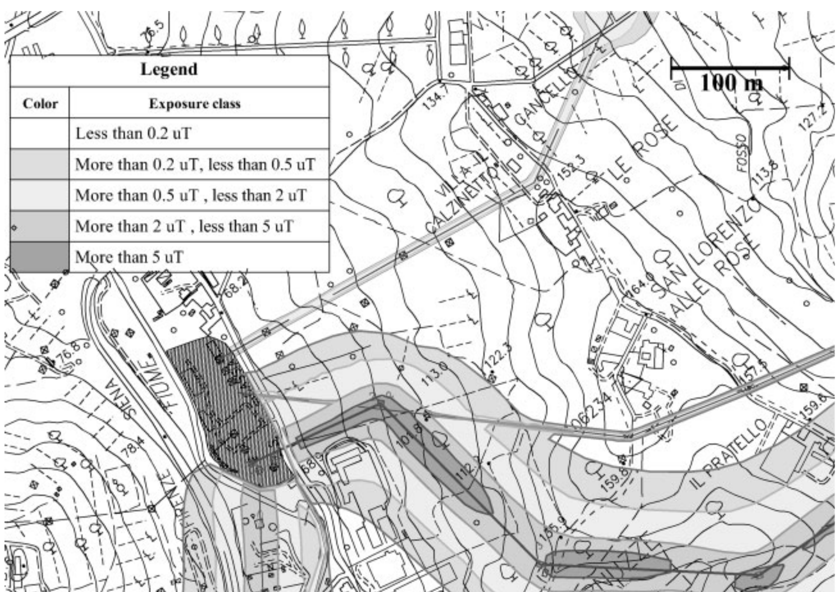

Figure 3. Example of a MFD contour plot in the vicinity of a substation. The plot is calculated using the coherent combination of the contributions from different power lines.

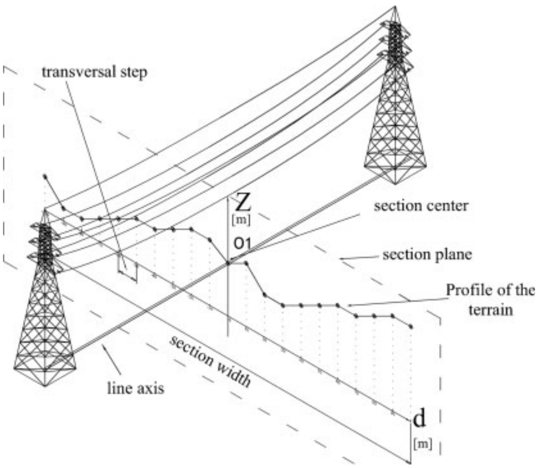

Figure 4. Definition of a section of terrain along a power line span. A section represents the terrain on a vertical plane transversal to the span axis.

to avoid overlapping among the portions of a plane occupied by different sections (see Figure 2). This occurrence is to be avoided as much as possible; otherwise, two conflicting representations of the same portion of territory may be introduced, producing potentially incorrect calculation results. Moreover, the absence of overlapping between sections facilitates automation of the process of tracing isolevel curves.

CONCLUSIONS

The main technical features of an advanced evaluation tool for estimating the MFD dispersed by power lines were presented. The tool overcomes the limitations of previously available software packages based on the direct application of standardized methods and is aimed at evaluating the MFD distribution in wide areas, taking into account both the land orography and the actual position, structure and cabling of the involved power lines. The tool uses contour maps to provide a compact and clear presentation method for calculated results.

REFERENCES

1. Comitato Elettrotecnico Italiano. *Guide to calculation methods of electric and magnetic fields generated by power-lines*. Norma CEI 211-4, Milan, Italy (1996) (in Italian).
2. Zoppetti, N. *Impatto ambientale dei campi generati dagli elettrodotti: sviluppo ed applicazione di un metodo innovativo per la valutazione*, Degree thesis, University of Florence, Italy (2002) (in Italian).
3. Andreuccetti, D., Zoppetti, N., Conti, R., Fanelli, N., Giorgi, A. and Rendina, R. *Magnetic fields from overhead power lines: advanced prediction techniques for environmental impact assessment and support to design*. In: Proceedings of 2003 IEEE Power Tech Conference, Bologna, Italy, 23–26th June (2003).
4. di Lavoro, G. *cEr/CeN: specifiche tecniche per la realizzazione del Catasto Elettromagnetico Nazionale e dei Catasti Elettromagnetici Regionali*. Rev. 3.1/ENEA, Rome, Italy (2001) (in Italian).
5. Shewchuk, J. R. *Triangle: engineering a 2D Quality Mesh Generator and Delaunay Triangulator*. In: First Workshop on Applied Computational Geometry, Philadelphia, PA (Philadelphia, PA: ACM), pp. 124–133 (1996).