Paper accepted for presentation at 2003 IEEE Bologna PowerTech Conference, June 23-26, Bologna, Italy

Magnetic Fields from Overhead Power Lines: Advanced Prediction Techniques for Environmental Impact Assessment and Support to Design

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***Abstract*– In this paper, the main features of a new advanced integrated approach to the problem of numerically predicting the distribution of the magnetic flux density generated by power lines is presented. This approach is based on an accurate model which takes into account both the three-dimensional structures of the power lines and the land altimetry. Two non-commercial computer programs have been developed in this framework, aimed to fulfil the needs of environmental control institutions and overhead line designers. In fact, they respectively allow to i) carry out thorough Environmental Impact Assessment (EIA) studies on new power lines and ii) assist the designer to calculate, in real time, the effects of his design options on the magnetic field levels.**

***Index Terms*-- Magnetic fields, Overhead lines, Design, Power transmission, Environmental Impact Assessment.**

I. INTRODUCTION

DURING the last few decades, increasing concern has been recorded in many industrialized countries towards exposures to power frequency (50/60 Hz) magnetic fields. Following up the results of a number of epidemiological studies (see [1] for a recent pooled analysis and [2] for an authoritative review of the scientific literature), population, media and institutions are getting more and more worried about the possible health effects of such exposures, even at levels as low as 0.4 ìT, in particular for what concerns children.

As a consequence of this situation, several local and central administrations have begun to adopt a precautionary approach, which in some cases is leading to regulate exposures to power frequency magnetic fields down to field levels in the range of a few tenths of microtesla. Many of these regulations usually require that preliminary evaluations were executed when new overhead power lines are planned or existing ones are subject to major modifications.

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In order to evaluate or verify compliance with these emerging regulations, both environmental and health control agencies and design departments of electric power companies are facing the need to theoretically evaluate magnetic field levels up to distances of the order of one hundred meters from the line axis, or even more. Geographic areas to be characterized are so large that computer models to be used for these applications should take the local land orography into account. The exact geometric structure of the power line should also be thoroughly considered, especially when the field evaluation points are close to the line axis. Finally, the precise line route should be reproduced in the computer model, if an accurate evaluation at points close to line turn angles is requested. Usually, these features are not present in the currently available software prediction tools.

II. NEEDS FOR ADVANCED PREDICTION TECHNIQUES

The problems described in the previous paragraph have emerged in a very evident way in some recent cases in which TERNA, the transmission company of ENEL Group, had to realize new overhead power lines. A particularly significant case is represented by the design of a 380 kV line to be set up in Tuscany, which has received large public opinion objections, even at international level, due to the fact that it crosses territories of high environmental value in the provinces of Firenze and Arezzo.

The need to properly face such kind of problems has highlighted the necessity to dispose of two different magnetic field prediction tools having a common approach. In one of them, which has been developed within ENEL Group by TERNA and CESI, the analysis of magnetic field distribution is strongly integrated in the line design tools, thus allowing to perform a preliminary evaluation of the possible alternatives in real time. The other tool, to be used off-line, is optimized for the characterization of a number of lines, in a given territory, and is mainly aimed at environmental impact assessment studies. It is the result of a collaboration between TERNA and IFAC-CNR which was specifically established to solve the above mentioned Tuscan case.

The two magnetic field prediction tools, which are based on similar methods to model the line spans, complete each other by fulfilling, at different level, both the internal design activities and the external ones concerning the relationships with local organizations and control authorities.

III. Environmental Impact Assessment

The IFAC research team suggests a new approach to the characterization of the 50 Hz magnetic field spreading from power lines to be used for environmental impact assessment purposes. It has been mainly worked out at IFAC-CNR as a graduation thesis [3] (and, as already said, in cooperation and with the financial support of TERNA). On the basis of this approach, a computer program has been developed, called PLEIA-EMF (Power Line Environmental Impact Assessment - Electric and Magnetic Fields), which fulfills most of the requests for a tool suitable for environmental evaluations. This program, which is currently undergoing further improvements and refinements, has been validated and successfully applied in the course of the environmental impact assessment (EIA) study relative to the already mentioned design of a new 380 kV power line in Tuscany, which is part of a general rearrangement of the power transmission and distribution network in an area of the provinces of Firenze and Arezzo.

Computer programs previously at our disposal for the analysis of the magnetic field generated by high voltage power lines were oriented to a manual entry of both line characteristics and field calculation loci; they usually did not allow to perform field evaluations over large areas in a simple way, especially when several line spans of different heights coexist in the same area; in general, isofield curves could not be traced and land orography could not be taken into account.

This kind of computer programs usually relied on a very rough ground representation and on a very simple model of the power line: the catenary path was not accurately reconstructed and line turn angles were often ignored. As a consequence, these programs presented several limitations which had to be overcome if accurate and specific evaluations, suitable for large area EIA, were sought.

For this reason, a new approach was worked out, able to:

1. set up an electronic archive of the data necessary to describe the electrical, topographic and mechanical characteristics of power lines;
2. manage a georeferenced Digital Terrain Model (DTM) which supplies the information for the correct positioning of field sources and calculation points in the 3D space;
3. make use of a magnetic field calculation algorithm able to interface both with the power line archive and with the digital terrain model;
4. specify in several alternative ways the field calculation loci, allowing for instance to calculate the field in a single georeferenced point or to draw a set of isofield curves directly into the digital topographic map. These curves represent a method for displaying results which conjugates accuracy, synthesis and reading easiness.

A. PLEIA principal characteristics

First of all, PLEIA-EMF is **specific**, in that it relies upon a detailed computer model of the actual power line (or lines) subjected to evaluation. Thank to the database approach, the contributions by a large number of power lines can be taken into account. The database structure was derived from the National Electromagnetic Database (NED) proposal. The original NED structure [4] was released in late 2001 by an ad-hoc working group, upon the completion of a two-year dedicated study. The NED project was managed by ENEA and involved several Italian research groups, among which the IFAC team. As a by-product of this project, the IFAC team also prepared an archive prototype, based on real data supplied by TERNA in the framework of the above mentioned EIA study. This prototype makes use of a proprietary database structure, which slightly differs from the official NED proposal in a few details, suggested by the on-field use of the archive.

Thanks to the database approach, PLEIA-EMF is able to access the georeferenced position of each power line tower, its height and orientation in space and the position of every fixing point on it. As also the catenary parameters of the conductors are stored in the database, PLEIA-EMF can effectively reconstruct the 3D position in space of each conductor of every span of every power line in the archive.

PLEIA-EMF is also **reliable**, as the results it provides are based on the actual power line characteristics coming from TERNA design files and on the 3D official digital topographic maps of the involved territories. In fact, PLEIA-EMF is able to directly interface itself with standardized digital topographic maps and terrain models, in order to collect and process information on land altimetry, useful to place in their correct 3D geographical position not only the power line components but even the points where the magnetic field has to be calculated.

Calculation of the magnetic flux density is based on the numerical integration of the Biot-Savart law in differential form (also called the First Laplace Formula), carried along the catenary path of every conductor of every span.

B. The archive structure

As a development of the above mentioned NED approach, the specifications for a database system able to store the characteristics of high voltage (above 132 kV) aerial or buried power lines were defined.

The database can accommodate all the data necessary to give support to an accurate magnetic field evaluation algorithm; it utilizes MySQL [5] as the DBMS (Data Base Management System) engine and a set of PHP procedures for data entry and maintenance.

The C and C++ programming languages were used as the development environment for:

1. the procedures for database access and information retrieval, based on a client-server approach;
2. the interface with the digital cartography in the AutoDesk standard AutoCad "dwg" format, via the OpenDWG software library [6];
3. the calculation of the magnetic field intensity in selected points.

The power line database contains four types of characteristic elements: **lines**, **spans**, **towers** and **conductors**. Adequate solutions were adopted in order to allow the database to describe both aerial and buried power lines with a common, consistent data structure.

One of the main objects of the database is the **line**, which is defined as *a segment of a power line without forks*; a line begins and ends at a power station or at a fork (a splitting point where three lines join). Thank to this definition, unique values of rated voltage and of phase currents can be assigned to each line.

A line is constituted by a number of spans; a **span** is defined as *a segment of a line between two consecutive towers*. A span is characterized by (a) the identifications of the two delimiting towers and (b) the set of **conductors** it contains; for each of these conductors, the electrical and mechanical characteristics (voltage, current, phase and catenary parameter) can be specified and stored in a appropriate database table.

Finally, the **towers** are *the structures at which the span conductors are attached.* A tower is characterized by its georeferenced position, height, orientation and by the position of every fixing point (the point where a conductor is attached) on it.

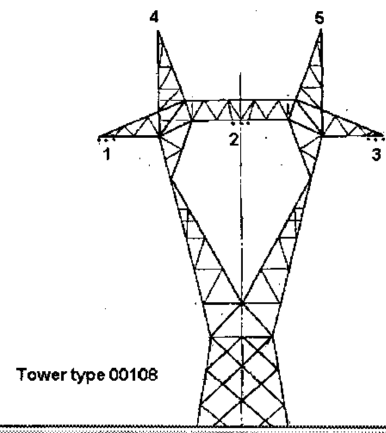
For each type of tower, a conventional "tower center" should be identified, usually situated on the tower main axis of symmetry, at the height of the lower conductor fixing point. The local coordinates of every fixing point (lateral and vertical displacements) with respect to the tower center are calculated and entered in the Table of Fixing Points as shown in Fig. 1, *making the assumption that all the fixing points lie on the same vertical plane which also contains the tower center.*

For each tower a "tower base" is also defined, corresponding to the ground foot of the vertical line passing through the above defined tower center. The absolute position of the tower base (XY plane rectangular geographic coordinates and altitude), the height of the tower center above the tower base and the orientation of the tower with respect to the geographical north are then stored in the Table of Towers as shown in Fig. 2.

This way, a complete mathematical model of the power line has been attained which allows to accurately represent (1) the absolute georeferenced position of the line, (2) the catenary path and (3) the electrical characteristics of every conductor of each of its spans.

C. Presentation of results

One of PLEIA-EMF more interesting characteristics is its **accessibility**, which means that its outcomes can easily be read and understood by non EMF-trained people, such as administrators or general public individuals. To achieve this feature, a proper data documentation and presentation method was designed, able to represent the distribution of the calculated field values in an accurate, exhaustive, synthetic and intelligible way. This method is based on the use of the so called "contour lines" and "contour plots". Contour lines are lines joining points (located at a fixed height above ground) where the same predefined value of the magnetic flux density is predicted; contour plots are the areas delimited by these lines. In each area, the flux density takes values lying between those associated to the area-delimiting contour lines. Contour lines are computed according to a proprietary algorithm, then directly drawn into the digital topographic map of the territory. In order to increase readability, contour plots are color-coded, i.e. different areas are filled with a conventionally colored (or gray-scaled) hatching, so that the same color is associated to the same flux density interval everywhere in the map.



TOW_TYP	N	HOR_DIS	VER_DIS
00108	1	-8.60	0.00
00108	2	0.00	1.00
00108	3	8.60	0.00
00108	4	-5.20	7.00
00108	5	5.20	7.00

Fig. 1 – Schematic diagram of the tower type 00108 and position of its fixing points (sample of the Table of Fixing Points).

TOW_ID	TOW_TYP	X_COORD	Y_COORD	ALTITUDE	HEIGHT	ORIENT
00004681	00105	1673737	4847026	43	30.00	124.00
00004682	00106	1673961	4846831	46	27.00	133.00
00004683	00104	1674200	4846588	62	24.00	123.00
00004684	**00108**	1674494	4846477	56	30.00	128.00
00004685	**00108**	1674718	4846144	53	33.00	135.00

Fig. 2 – Sample of the Table of Towers. The tower identification numbers are reported in the first column, the tower types in the second one, the topographic coordinates, heights and orientations in the following ones.

The algorithm used to build up the contour lines is based on the definition of a "computing project". The project lists the power lines involved in the calculation and specifies the intensity of the current on each of them, the magnetic flux density values for which the contour lines must be drawn and the height above ground to which the calculation refers.

The algorithm is also based on a proprietary representation of the ground conformation, called the "ground matrix", which is a set of 3D georeferenced points extracted from the DTM according to the method described below.

D. Ground representation

In order to build the contour lines, a proper ground representation model should be prepared. First of all, a power line is selected among the lines involved in the calculation (listed in the computing project). Following the path of this "main power line" of the project, a set of ground points (called the **ground matrix**) is prepared as follows.

Starting at the first tower of the main power line and continuing up to the last one, all the points spaced 20 m apart along the axis of the line are selected; these points are called "main ground points" of the project. These points constitute the core of the ground matrix. For each of them, two lateral rectilinear straddles called **sections** are considered, directed in the two opposite directions perpendicular to the line axis. Going along these sections with a 10 m step up to a distance of 200 m from the axis, more ground points are selected and added to the ground matrix. Each point in the ground matrix is identified through its XY plane geographical coordinates, which are also used to enter the DTM and determine the point altitude.

The DTM was kindly supplied by TERNA SpA. It represents the land orography of the area under study through a set of triangles whose vertexes have known coordinates and altitudes. In order to determine the altitude of a generic point in the ground matrix, first of all one has to find out at which triangle it belongs and then calculates its altitude by means of a linear interpolation among the vertexes of that triangle.

After all, the ground matrix comprises 100 sections and 2050 3D georeferenced points for every kilometer of power line; these points describe the conformation of an area of 0.4 km^2 along the line, with a mean value of more than 5000 points per square kilometer.

E. Building a contour line

The PLEIA-EMF procedure devoted to locate and map out contour line of a given magnetic flux density value explores every section in the ground matrix, looking for the points along it where the field intensity equals the sought value (within an assigned tolerance). At each point, the field value is calculated by means of the PLEIA core computational algorithm. Sections are sampled using a 1 meter sampling step, so that not only the points in the ground matrix are considered, but even a lot of intermediate points among them. The altitude of an intermediate point is evaluated as a linear function of the altitudes of the two closest ground matrix points.

As soon as a point with the sought field value is discovered, PLEIA immediately draws it into the digital cartographic map. When every section has been fully explored, these points should be connected in a single line. At present, this is only partially an automated process. A manual intervention is also required in some cases, for instance where significant contributes from several different power lines are present or where high field values are sought, producing a characteristic "island-shaped" contour line.

It is important to notice that, from a computational point of view, the construction of a contour line is taken back to multiple repeated applications of the PLEIA-EMF core algorithm for calculating the magnetic flux density generated by a given set of power lines in a point of given 3D coordinates.

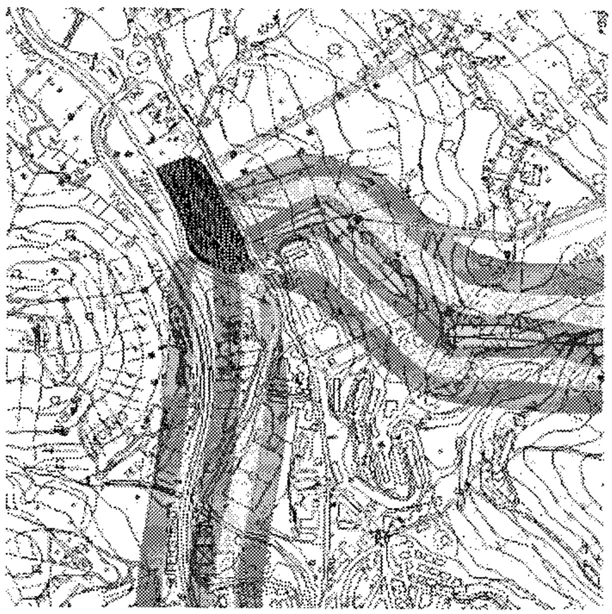


Fig. 3 – Example of a typical PLEIA-EMF outcome.
Moving away from the power line axis, zones with different gray hatching represent areas with decreasing magnetic flux density values.
The edges of the areas correspond to field values of 5 (inner edge) - 2 - 0.5 and 0.2 microtesla (outer edge).
In this examples, five power lines are simultaneously taken into account, two of which are 380 kV single circuit aerial lines and three of which are 132 kV single circuit buried lines.

F. Examples

Typical examples of PLEIA-EMF contour plots are presented in Fig. 3 and Fig. 4.

The former documents the possibility to include several power lines (five in the example) in a single computing project, while the latter is able to demonstrate the ability of the program to properly account for the land orography (hills and valleys) and for the presence of power line turn angles.

A few standard conditions were established in order to frame the evaluation process in a stable, known context.

They can be summarized as follows.

- All contour lines are relative to an height of 1 meter above ground, as suggested by a recent Italian national regulation (CEI 211-6, January 2001).
- Every evaluation considers the conductors to be in the EDS (Every Day Stress) condition: ambient temperature 15°C, no wind, no ice.
- Reference values for the contour lines were chosen so as to describe in a synthetic but sufficiently accurate and exhaustive way the environmental magnetic flux density distribution around a power line, from the line axis up to a

distance of the order of one hundred meters. Selected values are 0.2 – 0.5 – 2 and 5 microtesla.

These conditions were also applied in examples of Fig. 3 and Fig. 4.

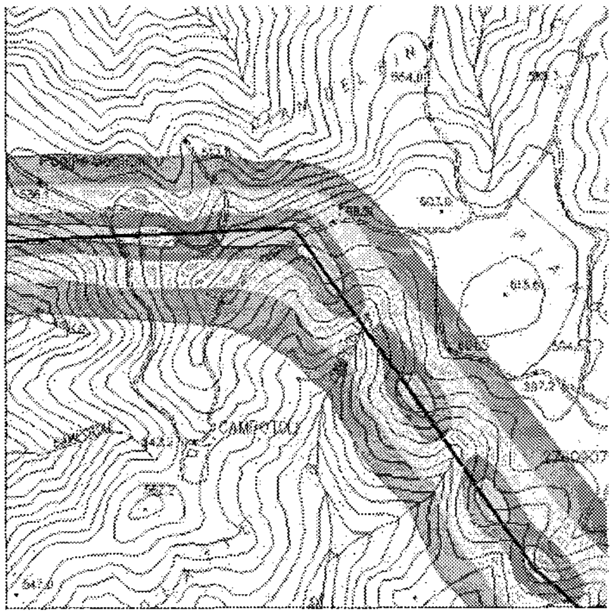


Fig. 4 – Example of a typical PLEIA-EMF outcome.
Moving away from the power line axis, zones with different gray hatching represent areas with decreasing magnetic flux density values.
The edges of the areas correspond to field values of 5 (inner edge) - 2 - 0.5 and 0.2 microtesla (outer edge).
In this example, just one 380 kV single circuit aerial power line is considered, making a turn while crossing an hilly region.

IV. SUPPORT TO POWER LINE DESIGN

In general, electricity companies are already equipped with suitable, more or less sophisticated, tools to identify, at design stage of new power lines, the proper combination of power line route, tower types and conductor heights above ground in order to work out an optimized design with respect to effectiveness, cost and compliance with international, national and local regulations. TERNA is no exception, having already developed very flexible and reliable computer programs for overhead line design. Nevertheless, as already said, the new constraints deriving from prescription on human exposure to magnetic fields have induced TERNA to enrich its design programs by a new tool, developed by CESI and called CAMEL, for the calculation of magnetic fields generated by the overhead lines under design, in accordance with the selected design parameters and considered in the real geographical environment.

A. General Requirements

TERNA's computer system for the design of overhead transmission lines, an essential part of which is now represented by the CAMEL program, basically consists of the following tools:

- AEROPOLIS: which is the program that, starting from aerophotogrammetry outputs and/or 3D digital orthophotos (Fig 5), permits to create the digital three-dimensional model of the terrain (DTM), as shown in Fig. 6. It also permits to generate the vertical profile of the ground for any possible route of the line.
- PARDO: which is the program that, starting from the above vertical profile, permits the best spotting of the towers, by utilising pre-designed structural elements and taking into account local constrains (Fig. 7). Together with AEROPOLIS, it permits, in real time and with a fully home-based job, the technical-economical comparison of all the possible alternatives.
- CAMEL: which extends the parameters of comparison, by providing a provisional evaluation of the magnetic fields associated to the various alternatives, aiming at the definition of the minimum impact solution.

As PLEIA-EMF program does, CAMEL calculates the magnetic field generated by the overhead line under study, by modelling the 3D catenary path of each conductor and taking into account the land orography. In the first instance, it interfaces the mechanical design package (AEROPOLIS-PARDO), to obtain the data concerning land altimetry, power line route, tower characteristics, and line catenary constant at sagging. Owing to the complexity of the data received by this interface, a visual representation of the overhead line thus acquired is almost mandatory. In second place the program should enable the line designer to evaluate the impact of its choices in "real time", and relate the results with territory evidences (buildings): this will imply the implementation of fast calculation algorithms, the adoption of memory parsimonious models for the terrain, the presentation of the calculated results without resorting to out-of-line post processing applications.

B. Input Interface.

As mentioned before, the new program, CAMEL, depends for its input data on an already existing application, with the additional constraints of utilising the output log files of that application. These output documents are created as formatted ASCII files, containing data relevant to identify the tower type, their location in space, the characteristics of each span; moreover, besides overhead line features, these data include the soil altitude along the vertical projections of each line conductors. In this way three altitude profiles along the line path are available (for instance, at the lateral distances of ±7.4 m and 0 m for a typical 380 kV single-circuit line). To complete the terrain description the mechanical design program (AEROPOLIS) is then requested to produce additional lateral profiles at distances of ±15 ±30 ±60 ±100 ±150 meters from the line axis. These altitude data are grouped into arrays, each referred to the pertinent line span: this representation has the advantage of low memory consumption, with respect to the more general representation based on triangles, and allows the implementation of fast interpolation algorithms to retrieve the altitude of a given point. For instance, a memory occupation of less than 3 Mbytes is needed to represent a line consisting of 40 towers and extending for 10 km.

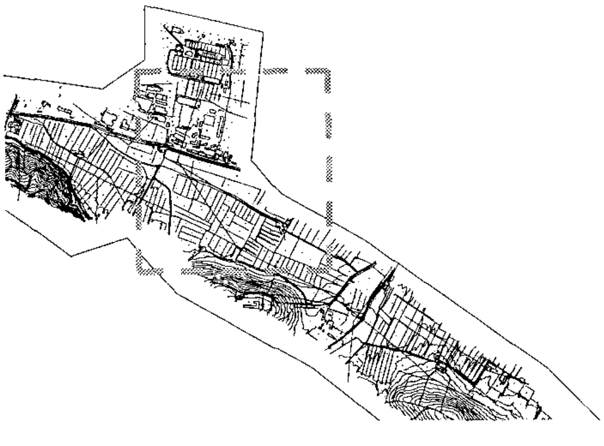


Fig. 5 - Example of aerophotogrammetry outputs of the territory to be crossed by a new overhead line (the dotted rectangle focuses the area chosen for subsequent examples).

Fig. 6 - Digital three-dimensional model of the terrain (DTM) of the zone within the dotted rectangle of Fig. 5.

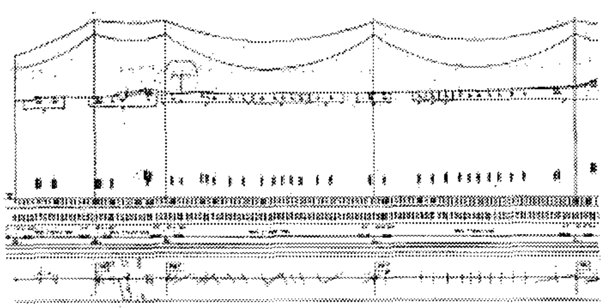


Fig. 7 - View of the vertical profile of the ground and of the line spans crossing the zone within the dotted rectangle of Fig. 5, together with local constrains.

The correctness of the whole input process is monitored through visual diagnostic tools which include the 3D representation of the catenaries of the whole line and the 3D outlines of every tower (Fig. 8); the designer has the possibility to check the tower types, their space position and the exact path of the line conductors.

Fig. 8 - Three-dimensional projection (enlarged view) of the line spans crossing the zone within the dotted rectangle of Fig. 5.

C. Calculation Algorithms.

The calculation of the magnetic field B in a given point P is performed by conventional numerical integration of the Biot-Savart law, carried over the various catenary paths of the whole line, which is suitably discretized. As a first step, given the (x,y) coordinates of P, its height (z coordinate) is obtained from the soil altimetry. The algorithm developed to this purpose first determines the line span from which the altitude data for the given point can be retrieved. In the next step, from the altitude matrix relative to this span, it finds the 4 points surrounding P(x,y), from which the desired altitude can be obtained by interpolation. Since this searching process is carried out through sorted data (as opposed to the case of a soil description based on triangles) the time required is small and its impact on the overall calculation time is negligible. To give an idea of the effectiveness of the time required to calculate the magnetic flux density, a real time display of B, tracking the mouse movements at the computer terminal, is possible even on a low speed, 200 MHz, processors. Following the punctual evaluation of B, the program has been provided with an original algorithm to realize magnetic field contour maps, where the contour lines are evaluated directly and not derived from a rectangular grid mapping. In this contour line construction, the distance between consecutive points is varied in function of the curvature, thus allowing the realization of high quality curves without wasting computer time. The actual steps range from 0.1 m to 5 m. The computer time required to generate contour lines varies between a few seconds to several minutes (1GHz processors), depending on the mapping area the user defines, typically with scales ranging from a few hundreds meters to several kilometers. The results can be displayed as a 3D projection or, as shown in Fig. 9, in a plane view where additional territory data are superimposed to the picture in order to identify the relationships with field levels.

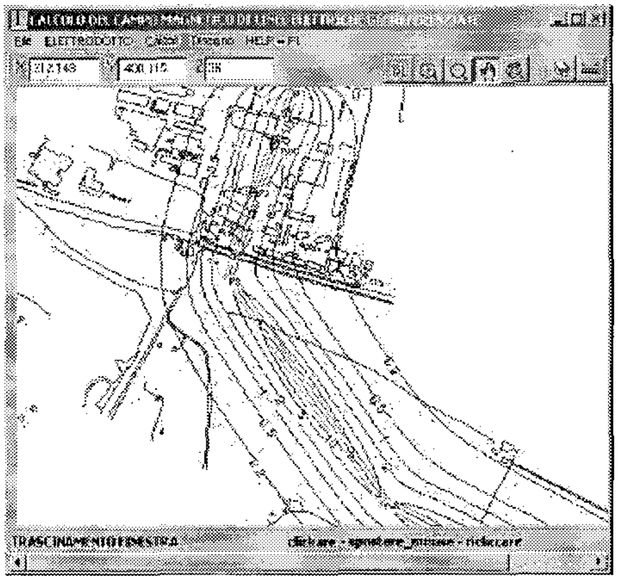


Fig. 9 - Plane representation of magnetic field contour lines (μT)) due to the line spans crossing the zone within the dotted rectangle of Fig. 5 and superimposed to territory features.

V. CONCLUSIONS

The magnetic field prediction tools described in this paper make it possible to manage the majority of the practical problems connected with both the realization of a new overhead line and the control and monitoring of those existing in the territory. Further developments are in progress in order to make such tools more efficient and to extend their application also in relation to the new Italian standards on human exposure to electromagnetic fields, whose publication is imminent. Thus, they will hopefully represent a valuable cooperation element for the electric companies and the organizations and authorities responsible for checking compliance with those standards.

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