SOFTWARE FOR EVALUATING MAGNETIC INDUCTION FIELD GENERATED BY POWER LINES: IMPLEMENTATION OF A NEW ALGORITHM

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ABSTRACT

The Regional Environment Protection Agency of Friuli Venezia Giulia (ARPA FVG, Italy) has performed an analysis on existing software designed to calculate magnetic induction field generated by power lines. As far as the agency's requirements are concerned the tested programs display some difficulties in the immediate processing of electrical and geometrical data supplied by plant owners, and in certain cases turn out to be inadequate in representing complex configurations of power lines. Furthermore, none of them is preset for cyclic calculation to determine the time evolution of induction in a certain exposure area. Finally, the output data are not immediately importable by ArcView, the GIS used by ARPA FVG, and it is not always possible to implement the territory orography to determine the field at specified heights above the ground.

Phidel®, an innovative software, tackles and works out all the above mentioned problems. The power line wires interested in its implementation are represented by polylines, and the field is analytically calculated, with no further approximation, not even when more power lines are concerned. Therefore, the obtained results, when compared with those of other programs, are the closest to experimental measurements. The output data can be employed both in GIS and Excel environments, allowing the immediate overlaying of digital cartography and the determining of the 3 and 10 µT bands, in compliance with the Italian Decree of the President of the Council of Ministers of 8th July 2003.

1 - INTRODUCTION

Since the Italian framework law [1] (Establishment of exposure limits, attention values, and quality goals to protect the population against power frequency (50 Hz) electric and magnetic fields generated by power lines) took effect, it had been necessary to investigate the issue of the calculation of such fields, to evaluate both the population exposition and the respect bands extension. These are now determined on the basis of the extensions of volumes of root mean square value of magnetic field strength, and not any more as a fixed distance from the wires.

Thus, ARPA FVG analyzed the more common software (CMagnetico by Istituto Trentino di Cultura- IRST, CAMPI [2] by prof. Daniele Andreuccetti of "Nello Carrara" Applied Physics Institute, LINATCTN by ARPA Piemonte, NIR-Calcolo ELF by Stefano de Donato [3]) for evaluating the magnetic induction field used by other Environment Protection Agencies in Italy. For each, the calculation method, the adopted frame of reference, the sampling region, the electric and geometric input data, the kind of presentation of output data, the programming language, the system requirements and the further available options were studied.

The analyzed products give predictions according to measurements, but almost all present insurmountable limits: they does not allow to evaluate fields generated by complex configurations (typically with intersecting lines) [4], it is not seldom possible to consider the current phase shifts of different lines, nor to execute a cyclic calculation on a data set regarding the line history. For these reasons a new software, called Phidel, had been realized. It refines the calculation algorithm and arranges data in a properly formatted output. To simplify the input of electric and geometric data, the software had been designed referring to the power lines database developed by the Agency and to the typology of data supplied by the plants owners [5].

2 - THE REQUIREMENTS OF THE NEW SOFTWARE

The analysis of other software and the structure of the data available by the Agency, brought to carry out in Phidel the following features:

- respect of Report No. CEI 211-4 [6] requirements;
- modularity, that is the possibility to operate on intermediate steps to modify data without restarting the whole input procedure, in case of modifying just a few parameters;
- saving data as text files at every step; to easily view and modify them;
- compatibility with available geometric and electric data;
- fast code execution;
- minimization of geometric approximations in the catenary characterization;
- graphic user interface to simplify the input data;
- possibility to elaborate external data arrays referred to phases and currents (or, in an equivalent way, to voltages and powers) to determinate the historical evolution of the field, also in presence of different power lines (batch modality).
- Field calculation in points, straight paths or planes, with coordinates origin, dimensions and sampling step specifiable by the user, with no two-dimensional sectioning [7];
- Possibility to specify two angles named ϕ and ψ (as in Figure 1) to calculate the field on inclined planes respect to the given frame of reference. Through this option, it is possible to obtain the magnetic induction values of vertical planes orthogonal to the span, and so determining the respect bands for the limit values specified by the current Italian law.

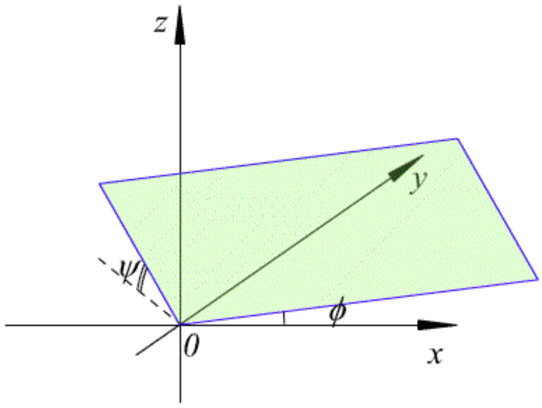

Figure 1 – Angles referred to an inclined calculation plane.

The project described in the following sections had been developed on the basis of the above described features. The only introduced approximations are referred to the span discretization and the hypothesis of the land transparent to the magnetic field [6, 8].

3 - THE CALCULATION ALGORITHM

The procedure which brings to the problem solution, implemented in Phidel code, is described in this section. The involved steps are summarizable as follows:

- span approximated by a broken line done by a finite number of determined length segments;
- calculation of the field produced by each segment;
- sum of all these contributions to obtain the total field;
- determination of the field versor;
- calculation of root mean square value of magnetic field strength.

3.1 - The catenary characterization

The curve a hanging flexible wire assumes when supported at its ends is called catenary and is analytically represented by an hyperbolic cosine function. Its form depends on a parameter (in the following indicated by a) defined as ratio between tension and linear weight (usually at a temperature of 40° C):

$$z(x) = b + a\cosh\left(\frac{x - x_0}{a}\right) \tag{1}$$

x_0 indicates the curve vertex coordinate, while the parameter b determinates the quote positioning.

When the coordinates of the suspension points, $(0, z_1)$ and (L, z_2) (see Figure 2 (a)), and the constant a are known, x_0 is analytically determined as:

$$x_0 = -a\ln\frac{\frac{z_2 - z_1}{a} + \sqrt{\left(\frac{z_2 - z_1}{a}\right)^2 + e^{-\frac{L}{a}}\left(e^{\frac{L}{a}} - 1\right)^2}}{e^{\frac{L}{a}} - 1} \tag{2}$$

and it is then possible to obtain b substituting the coordinates of one extreme in equation (1).

When the curve is defined, the coordinates of the extremes of every segment approximating the catenary are shown in Figure 2 (b). The span of length L is divided into segments having projection l on the ground. Indicating the coordinates of the suspension point of the first pylon by X_0, Y_0 and Z_0, the suspension extremes of the k^{th} segment are given by:

$$x_k = X_0 + kl\cos\phi \tag{3}$$

$$y_k = Y_0 + kl\,\mathrm{sen}\,\phi \tag{4}$$

while z_k is obtained by (1), since x_k is known.

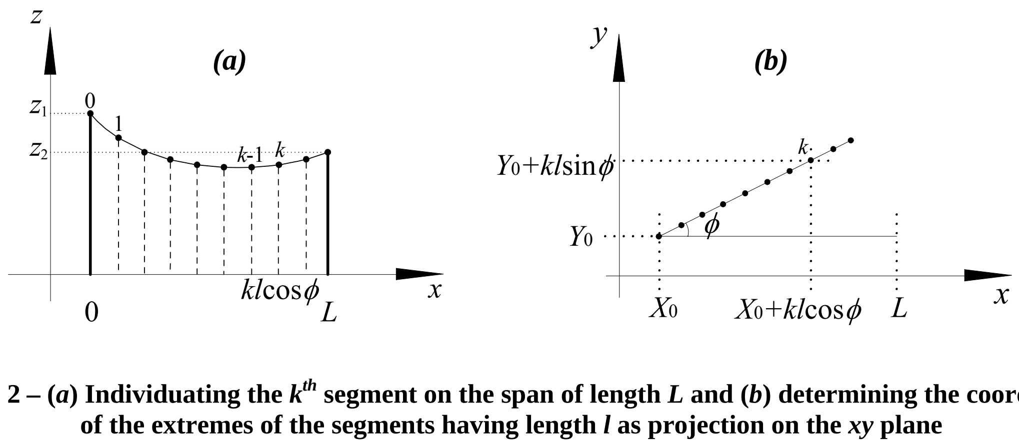

Figure 2 – (a) Individuating the k^{th} segment on the span of length L and (b) determining the coordinates of the extremes of the segments having length l as projection on the xy plane

3.2 - Field generated by a current-carrying segment

To calculate the induction magnetic field generated by a current-carrying segment, the Biot-Savart law is applied:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_C \frac{I(\vec{r}\,')d\vec{l} \times \vec{R}}{R^3} \tag{5}$$

where $\vec{R} = \vec{r} - \vec{r}\,'$ is the shift vector from the point $\vec{r}\,'$ in which the wire element $d\vec{l}$ carrying a current $I(\vec{r}\,')$ stands to the point $\vec{r}$ where the field is calculated. Considering the case of a straight finite wire oriented along the x axis, the field produced by the current element $Id\vec{l} = Idx'\mathbf{i}$ (see Figure 3) is given by [9]:

$$d\vec{B} = \frac{\mu_0 Idx'}{4\pi R^3}\mathbf{i}\times\left(-x'\mathbf{i} + y\mathbf{j} + z\mathbf{k}\right) = \frac{\mu_0 Idx'}{4\pi R^3}\left(y\mathbf{k} - z\mathbf{j}\right) \tag{6}$$

where **i**, **j** and **k** are the versors referred to the Cartesian axes. The radius vector, from the coordinates origin to the point Q in which the field has to be calculated, is given by $\vec{\rho} = y\mathbf{j} + z\mathbf{k}$, and then $\vec{\rho}\cdot\vec{B} = 0$: the field lines are consequently perpendicular to the radius vector, and they describe circumferences around the axis containing the wire (see Figure 3). In fact, this is a cylindrical symmetry problem.

It is convenient, for the following, to define the versor:

$$\hat{\varepsilon} \equiv \frac{\left(y\mathbf{k} - z\mathbf{j}\right)}{\rho} \tag{7}$$

Its point of application (where the field has to be calculated) is known, and ρ is the distance from the axis containing the wire.

Then, the (6) becomes:

$$d\vec{B} = \frac{\mu_0 I\rho dx'}{4\pi R^3}\hat{\varepsilon} \tag{8}$$

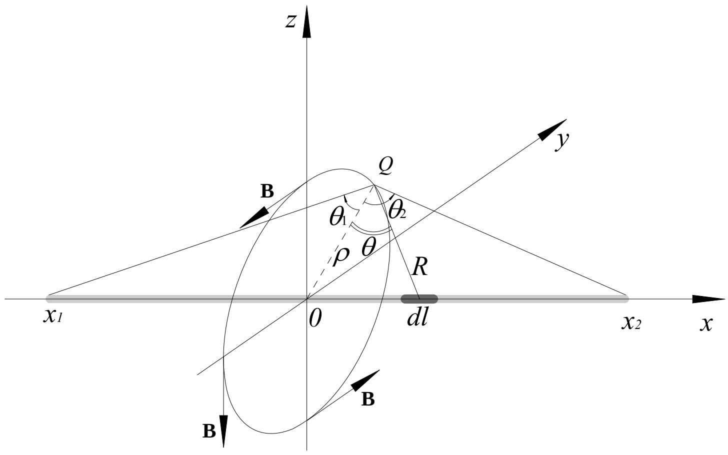

Figure 3 - Determining the field in the *yz* plane.

Using the angles θ, θ_1 and θ_2 as defined in Figure 3, substituting in the (8) and integrating along the wire, it follows:

$$\vec{B} = \frac{\mu_0 I}{4\pi\rho}\left(\sin\theta_2 - \sin\theta_1\right)\hat{\varepsilon} \tag{9}$$

This relation does not depend on the frame reference, and it is valid also out the yz plane. It is possible to demonstrate [10] the (8) assumes the following simplified expression:

$$\vec{B} = \frac{\mu_0 I}{4\pi}\eta\hat{\varepsilon} \tag{10}$$

where $\eta = \dfrac{\left(\sin\theta_2 - \sin\theta_1\right)}{\rho}$ is a geometric term and $\hat{\varepsilon}$ is the field versor.

This quantity, calculated in the case of a 40 m length wire, carrying 1600 A, is shown in Figure 4:

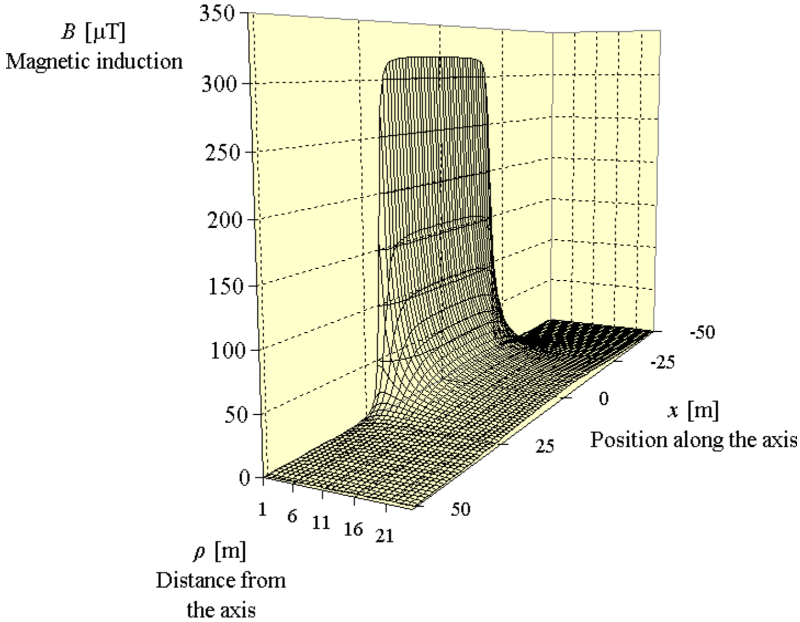

Figure 4 – Field generated by a 1600 A current-carrying segment in function of position.

In the case of a sinusoidal alternate current of the form $I(t) = I_0 \sin(\omega t + \varphi)$, where I_0 is the peak current, ω the angular frequency and ϕ the phase angle, it is possible to obtain from the (10) the field generated by the i^{th} segment at the time t:

$$\vec{B}_i(t) = \frac{\mu_0}{4\pi} I_i \sin(\omega t + \varphi_i)\eta_i \hat{\varepsilon}_i \tag{11}$$

3.3 - Root Mean Square Field calculation

In a sinusoidal alternate regime, as in the power line technology, the magnetic field amplitude changes cyclically with the same frequency of the generating current. In the case of many three phases power lines, the three spatial components of the field are not generally in phase among them, and the amplitude and direction of the resulting vector consequently change in the time.

Thus, the quantity the legislation [1, 6] refers to, and given by the instruments, is the Root Mean Square (*RMS*) magnetic induction field, defined as:

$$B^{RMS} \equiv \sqrt{\frac{1}{T}\int_0^T B^2(t)dt} \tag{12}$$

where T is the period associated to the 50 Hz mains frequency. This value will now be obtained substituting the (11) into (12):

$$B^{RMS} = \frac{\mu_0}{4\pi}\sqrt{\frac{2}{T}\sum_{i,j} I_i^{RMS} I_j^{RMS} \eta_i \eta_j \hat{\varepsilon}_i \cdot \hat{\varepsilon}_j \int_0^T \sin(\omega t + \varphi_i)\sin(\omega t + \varphi_j)dt} \tag{13}$$

where the i and j indices in the sum are segment indices. A consequence of the discretization is the absence of references to the single conductor, remembering that all the segments describing it are currying the same current $\sqrt{2} I_i^{RMS} \sin(\omega t + \varphi_i)$.

Defining the tensorial element A_{ij} as:

$$A_{ij} = \prod_{k=i,j} I_k^{RMS} \eta_k \hat{\varepsilon}_k \tag{14}$$

and solving the integral under root square in (13), it is finally obtained [10]:

$$B^{RMS} = \frac{\mu_0}{4\pi} \sqrt{\sum_{i,j} A_{ij} \cos(\varphi_j - \varphi_i)} \tag{15}$$

which represents the final equation for the *RMS* field employed in Phidel.

It is now possible to notice the dependence of the *RMS* magnetic induction on the term $\cos(\varphi_j - \varphi_i)$, depending on the relative phase among the conductors, and on the term A_{ij} depending on the currents and the system geometry.

4 - THE STRUCTURE OF THE SOFTWARE

Phidel is divided into two distinct parts [11], concerning the input of the data and their processing, which prelude to the following visualization in GIS (Geographic Informative System) environment, or to the worksheet elaboration. The two sections, concerning to particular actions, had been developed in different programming languages, for practicalness and execution speed reasons.

An advanced option executes the calculation in batch modality, automating the computing process of big amounts of data referred to the temporal progress of electric quantities of considered power lines, to obtain the magnetic field evolution in a specified point.

4.1 – Data input

The part concerning the electric and geometric data input had been developed in PHP4, an open source scripting language aimed at web programming. It is server side, which means the script are executed on the server, and from there the output is sent to the client browser as HTML file. The only software requirements (for using PHP4 as server side scripting) consist in a web server, the PHP module and, of course, a browser.

Thanks to the PHP potentialities, the pages for the data input and the relative fields are dynamically created at any one time, depending on the user's requests. The convention used for the input data depends on the study done on the other available software, but it moreover considers the power lines database built by ARPA FVG, and consequently the data owned by the Agency.

The input happens according to the following schema, which describes the data required by each of the three steps:

- input of number of power lines;
- per each line: name, number of pylons and wires, current and length of the segment approximating the span;
- per each pylon: altitude, coordinates, and angle referred to the frame of reference; per each wire it is necessary to specify the phase (*R*, *S* or *T*), the suspension point height, its distance from the pylon, the parameter a and the length of the insulator chain.

Finally, the user writes the project name, which will be used with current data and hour, to generate a backup file.

When input data are confirmed, a check on every field signals eventual missing or inconsistent values, to let the user to complete or to correct the input.

Finally, data are saved on an ASCII file. It can eventually be modified in only some parameters, for example changing current or altitude values, without repeating the whole input procedure, to re-execute the calculation for a similar configuration.

4.2 – Data processing

The data processing to evaluate the *RMS* magnetic induction field using (15) requires a larger amount of system resources. This implementation had consequently been developed using Visual C++, a compiled programming language which allows to operate in a visual environment to design the user interface.

The code complexity and required memory change quadratically as function of the total number of segments.

Thus, the choice of this length is relevant in case of complex configurations, with a large number of involved spans. It is however necessary to verify that the loss in precision does not excessively affect the final result. Finding a good compromise between calculation precision and employed resources (time and RAM memory) is consequently essential.

The software reads the data file, elaborates it and creates a text file as output. It is build as a four columns matrix: two of them for the coordinates, the third for the altitude and the fourth for the *RMS* magnetic induction.

4.3 - The visualization

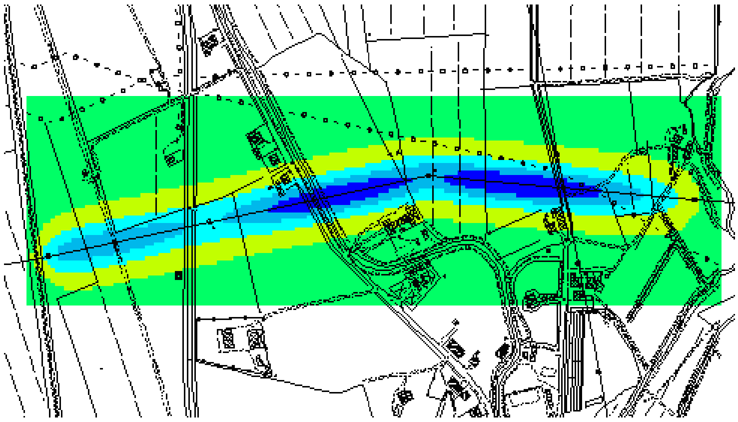

Figure 5 - Output data visualization in GIS environment.

The output file is compatible with the ArcView GIS software: it displays on video (see Figure 5) the field values overlapped to cartography.

In this way, when the field values in the visualization mask are correctly set, it is immediately possible to determine the extension of the respect bands given by [1].

4.4 – Time evolution calculation

An advanced Phidel option (the so-called batch modality) allows to evaluate the time evolution of magnetic induction in a point, using the historical values of electric quantities of Very High Voltage (220 and 380 kV) power lines.

The software works out the file with the system electric and geometric data, and a text file with the recordings of the power line owner.

The Figure 6 shows the time evolutions of values calculated by Phidel (in orange), and the measurements obtained by a PMM8055S continuous area monitor station positioned in proximity of a double line [2]. The $\widetilde{\chi}^2$ test on these data sets confirms the algorithm validity, giving as result $\widetilde{\chi}^2_{5182} = 0.6$.

Figure 6 – Time evolution of measured field (bright blue line) and prevision by Phidel (orange line).

This software feature also allows to evaluate the median value (as Articles 3 and 4 from [1]) of magnetic induction from electric quantities, when it is not possible to use the above mentioned monitor station. It is in fact necessary to consider the relative phase shifts among currents, because in presence of different lines it is not possible to obtain the field median from the only median values of currents, without considering the relative phase shifts among them, nor using a short term measurement [2].

5 - THE COMPARISON AMONG THE SOFTWARE

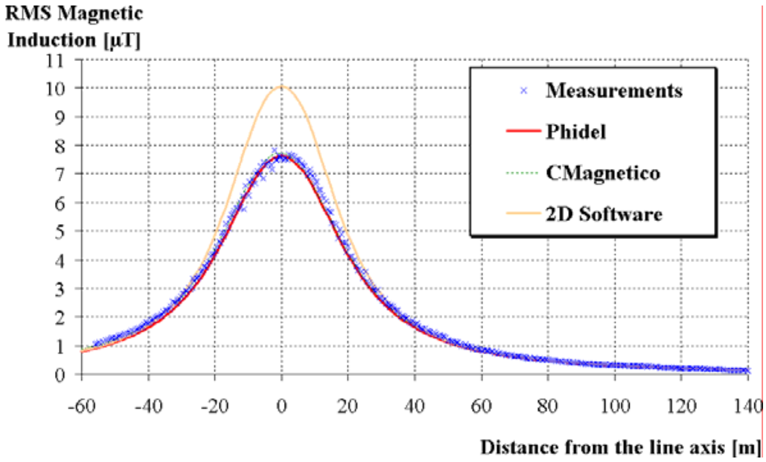

Figure 7 – Comparison between experimental data and software results.

The results obtained by analyzed software had been compared with measurements done near two 380 kV power lines [10] (see Figure 7) using the LINDA system, made by an EMDEX II field meter (by Enertech Consultants) fixed on a mobile support, supplied by an odometer. This records simultaneously the field values, the time and the information about the path.

Three among the above considered software (CAMPI [2], LINATCTN and NIR [3]) work in two dimensions: thus, they allow only the calculation along paths orthogonal to the power line, and the comparison to experimental data in case of oblique trajectories is not possible. These software approximate moreover the wires as parallel and infinite, and they does not allow to consider the span form, nor the line trajectory.

The use of Phidel concurs to economize on time, because it gives the required data with no other elaboration to consider the angle of the trajectory path relatively to the normal to the line axis: in this way, the comparison with experimental data is immediate.

The comparison of the $\tilde{\chi}^2$ values, shown in Table 1 for each of the considered software, shows the according between measurements and the software output data, demonstrating that data given by Phidel are more reliable.

Table 1 – Evaluation of various software reliability.

Power line	Phidel	CMagnetico	Software 2D
21356 (380 kV)	$\tilde{\chi}^2_{260}=0.6$	$\tilde{\chi}^2_{260}=0.6$	$\tilde{\chi}^2_{260}=2.7$
21347 (380 kV)	$\tilde{\chi}^2_{75}=0.7$	$\tilde{\chi}^2_{75}=1.0$	$\tilde{\chi}^2_{75}=2.3$

6 - OROGRAPHIC EVALUATION

A useful utility implemented in Phidel allows to execute orographic evaluations of the field values, as described in the following. The first step is the determination of a digital terrain model (DTM) using the quoted elements from the digital cartography. The interpolating algorithm is the inverse of distances, allowing the user to define the number of nearest neighbours to implement in the calculation and the exponent weighting the distances.

This example describes a situation with two 220 kV (green lines) and one 132 kV (light blue lines) power line (Figure 8, on the left), starting from the same primary transformation station (in Somplago, Italy). This had been chosen for the presence of several power lines and the particular territory orography (the station is set between two mountains and in front of a lake, in which there are no quoted points in the digital cartography).

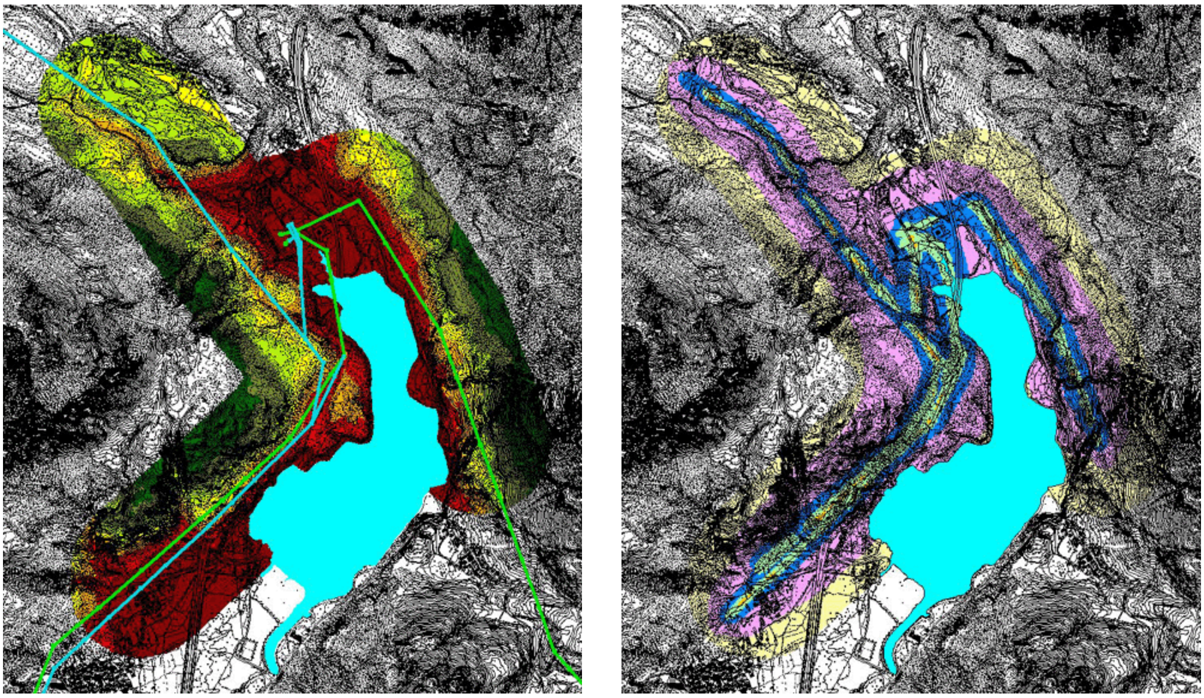

Figure 8 – Determination of territory orography (on the left) and magnetic induction (on the right).

The evaluated points belong to a regular grid, which extension can be later reduced following an irregular contour desired by the user, as shown in Figure 8 (on the left).

The result of Phidel orographic evaluation is shown in Figure 8 (on the right): it allows to evidence the 3 μT level for the induction magnetic field at a desired height, as requested by [1].

7 - CONCLUSIONS

The necessity to calculate magnetic induction in complex power lines configurations has brought to develop a new tool, called Phidel, which makes best the data input, processing and visualization procedures, and allows to consider systems with more lines, both aerial and underground, and to evaluate the extension of field volumes over the values specified by the current Italian laws using the only approximation of the span discretization.

The algorithm implements the Biot-Savart law, and it is then conform to the Report No. CEI 211-4 [6] requirements. The software gives output data compatible with the GIS software usedby the agency, and the batch modality allows to elaborate large amounts of data in complex configurations.

The implementation in PHP4 and through the Visual C++ programming language lets at last to gain in versatility, portability and efficiency, giving to the user a suitable graphic interface at the same time.

The inverse of distances algorithm, used in the orographic evaluation section, allows the user to calculate the field values in a grid of quoted points at a fixed height on the ground: this immediately brings to decide if the law limits are respected or not.

Finally, the comparison with the software used in the other Regional Agencies has shown a greater agreement with measurements and a better suitability to the data given by the plants owners.

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