A TECHNICAL NOTE ABOUT PHIDEL: A NEW SOFTWARE FOR EVALUATING MAGNETIC INDUCTION FIELD GENERATED BY POWER LINES

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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. Phidel, an innovative software, tackles and works out all the above-mentioned problems. 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 the 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 8 July 2003.

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] has taken effect, it has been necessary to investigate the issue of the calculation of such fields, to evaluate both the population exposure and the respect bands extension. These are now determined on the basis of the extensions of volumes of the root mean square (RMS) value of the magnetic field strength and no longer as a fixed distance from the wires.

Thus, ARPA FVG analysed the most 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]) used for the evaluation of the magnetic induction field adopted by other Environment Protection Agencies in Italy. For each one, the calculation method, the adopted reference frame, the sampling region, the electric and geometric input data, the output data presentation, the programming language, the system requirements and the further available options were studied.

The analysed products give predictions according to measurements, but almost all of them present insurmountable limits: none of these systems allows to reliably evaluate fields generated by complex configurations (typically with intersecting lines)[4], it is often not possible to consider the current phase shifts of the different lines, or to execute a cyclic calculation on a dataset concerning the line history. For these reasons a new software, Phidel, has been developed. It refines the calculation algorithm and arranges data in a properly formatted output presentation. To simplify electric and geometric data input, the software has been designed referring to the power line database developed by the Agency and to the typology of the data supplied by the owners of the plants[5].

THE REQUIREMENTS OF THE NEW SOFTWARE

The analysis of another software and the structure of the data available to the Agency led to have the following features carried out by Phidel:

- compliance with the requirements outlined in Report No. CEI 211-4[6];
- modularity, which is, the possibility to modify data at intermediate steps without restarting the whole input procedure, in case only a few parameters are to be modified;
- save data as text files at every step, to easily view and modify them;
- compatibility with available geometric and electric data;
- fast code execution;
- minimisation of geometric approximations in the catenary characterisation;
- graphic user interface to simplify data input;
- possibility to process external data arrays referred to phases and currents (or, similarly, voltages and powers) to determine the historical evolution of the field, also in presence of different power lines (batch modality);

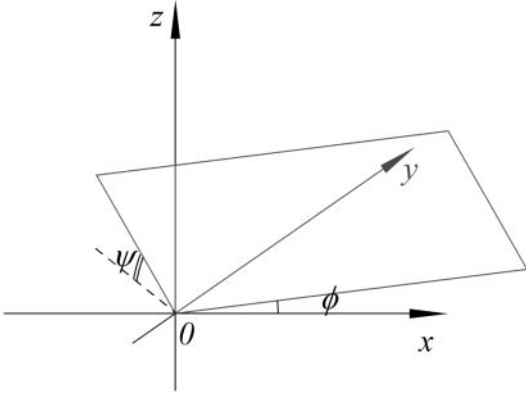
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Figure 1. Angles referred to an inclined calculation plane.

- field calculation in points, straight paths or planes, with coordinate origin, dimensions and sampling step specifiable by the user, with no 2-D sectioning[7];
- possibility to specify two angles ϕ and ψ (as in Figure 1) to calculate the field on inclined planes with respect to the given reference frame. Through this option, it is possible to obtain the magnetic induction values of vertical planes orthogonal to the span, and therefore determine the respective bands for the limit values specified by the current Italian law.

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

THE CALCULATION ALGORITHM

The procedure which leads to the solution of the problem, implemented in Phidel code, is described in this section. The steps involved can be summarised as follows:

- span approximated by a broken line made up of 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 the RMS value of the magnetic field strength.

The catenary characterisation

The curve a hanging flexible wire assumes when supported at its ends is called catenary and is analytically represented by a hyperbolic cosine function. Its form depends on a parameter (in the following

indicated as a) defined as the ratio between tension and linear weight (usually at a temperature of 40°C):

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

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

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

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

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 2b. 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

$$x_k = X_0 + kl \cos \phi \qquad (3)$$

$$y_k = Y_0 + kl \sin \phi \qquad (4)$$

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

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:

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

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 $Id\vec{l} = Idx'\boldsymbol{i}$ (Figure 3) is given by[9]

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

where $\mathbf{i}$, $\mathbf{j}$ and $\mathbf{k}$ 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 $\vec{\rho} = y\boldsymbol{j} + z\boldsymbol{k}$, 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 (Figure 3). In fact, this is a cylindrical symmetry problem.
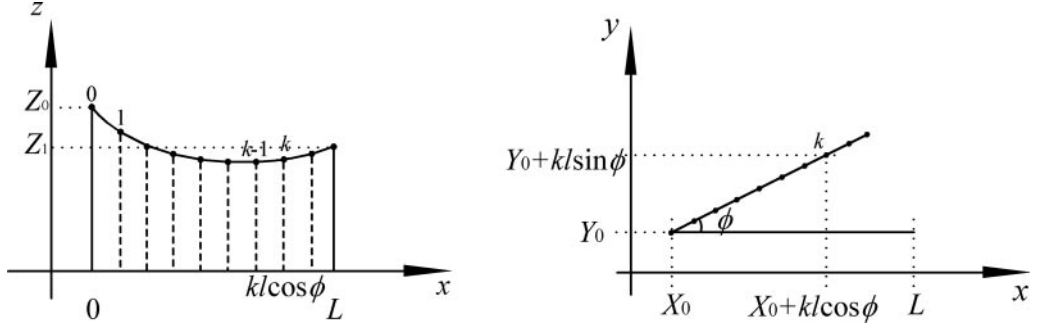
Figure 2. (a) Individuating the k-th segment on the span of length L and (b) determining the coordinates of the extremes of the segments having length l as projection on the xy plane.
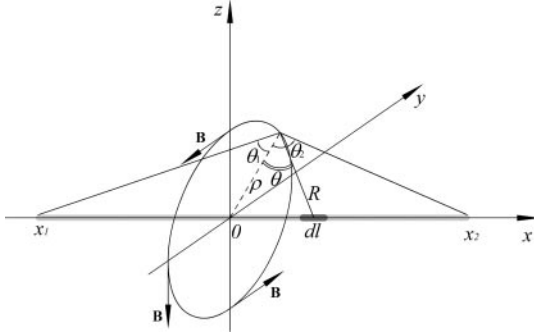

Figure 3. Determining the field in the yz plane.

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

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

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

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, (6) becomes

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

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

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

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

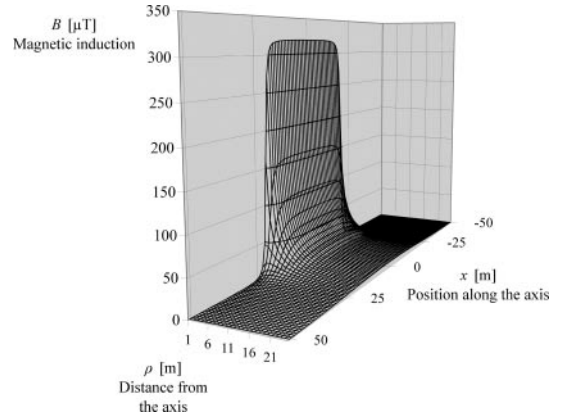$$\vec{B} = \frac{\mu_0 I}{4\pi}\eta\hat{\varepsilon}, \tag{10}$$

where $\eta = [(\sin\theta_2 - \sin\theta_1)/\rho]$ 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.

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 (10) the field generated by the i-th segment at the time t:

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

RMS field calculation

In a sinusoidal alternate regime, as in power line technology, the magnetic field amplitude changes cyclically with the same frequency as the generating current. In the case of many three phase 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 time.

Thus, the quantity the legislation[1,6] refers to, and given by the instruments, is the RMS magnetic induction field, defined as follows:

$$B^{\mathrm{RMS}} \equiv \sqrt{\frac{1}{T}\int_0^T B^2(t)\mathrm{d}t},\qquad(12)$$

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

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

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

Defining the tensorial element A_{ij} as

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

and solving the integral under root square in (13), we finally obtain[10]

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

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.

THE STRUCTURE OF THE SOFTWARE

Phidel is divided into two distinct parts, concerning the data input and their processing, which prelude to the following visualisation in GIS (Geographic Informative System) environment or to the worksheet representation. The two sections, concerning particular actions, have been developed in different programming languages, for practical usage and execution speed reasons.

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

Data input

The part concerning the electric and geometric data input has been developed in PHP, an open source scripting language aimed at web programming. It is server side, which means the scripts are executed on the server, and from there the output is sent to the client browser as an HTML file. The software requirements (for using PHP as server side scripting) consist of 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 time, depending on the user's requests. The convention used for the input data depends on the study carried out by the other available software, but it also considers the power line database laid out by ARPA FVG, and consequently the data owned by the Agency.

Data input is carried out according to the following schema, which describes the data required by each of the three steps:

- input of number of power lines;
- for each line: name, number of pylons and wires, current and length of the segment approximating the span;
- for each pylon: altitude, coordinates and angle referred to the frame of reference; for 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 the input data are confirmed, a check on every field signals eventual missing or inconsistent values, in order to let the user either complete or correct the input.

Finally, the data are saved on an ASCII file. This can be eventually modified in some parameters, e.g. changing the current value, without repeating the whole input procedure, to re-execute the calculation for a similar configuration.

Data processing

The data processing to evaluate the RMS magnetic induction field using (15) requires a larger amount of system resources. This implementation has therefore 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.
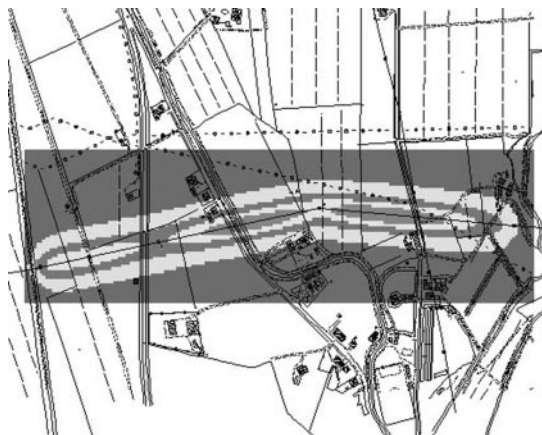
Figure 5. Output data visualisation in GIS environment.

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

Table 1. Evaluation of various software reliability.

Power line	Phidel	CMagnetico	2-D software
21 356 (380 kV)	$\tilde{\chi}^2_{260} = 0.6$	$\tilde{\chi}^2_{260} = 0.6$	$\tilde{\chi}^2_{260} = 2.7$
21 347 (380 kV)	$\tilde{\chi}^2_{75} = 0.7$	$\tilde{\chi}^2_{75} = 1.0$	$\tilde{\chi}^2_{75} = 2.3$

Thus, the choice of their 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 structured as a four columns matrix: two of them for the coordinates, the third for the altitude and the fourth for the RMS magnetic induction.

The visualisation

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

In this way, when the field values in the visualisation mask are correctly set, it is immediately possible to determine the extension of the respect bands given by Ref. (1).

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.

Figure 6 shows the time evolutions of values calculated by Phidel (the bright line) and the measurements (dark line) obtained b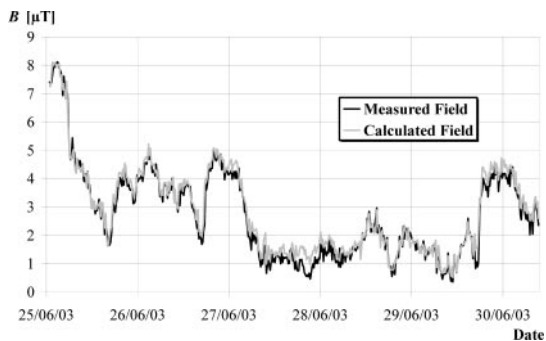y a PMM 8055S continuous area monitor station positioned in proximity of a double line[2]. The $\tilde{\chi}^2$-test on these datasets confirms the algorithm validity, giving as result $\tilde{\chi}^2_{5182} = 0.6$

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 only from the median values of currents, without considering the relative phase shifts among them, or using a short-term measurement[4].

THE COMPARISON AMONG THE SOFTWARE

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

Three among the above considered software products (CAMPI[2], LINATCTN and NIR[3]) work in two dimensions: thus, they only allow the calculation along paths orthogonal to the power line, whereas, the comparison to experimental data in case of oblique trajectories is not possible. Moreover, these software products approximate the wires as parallel
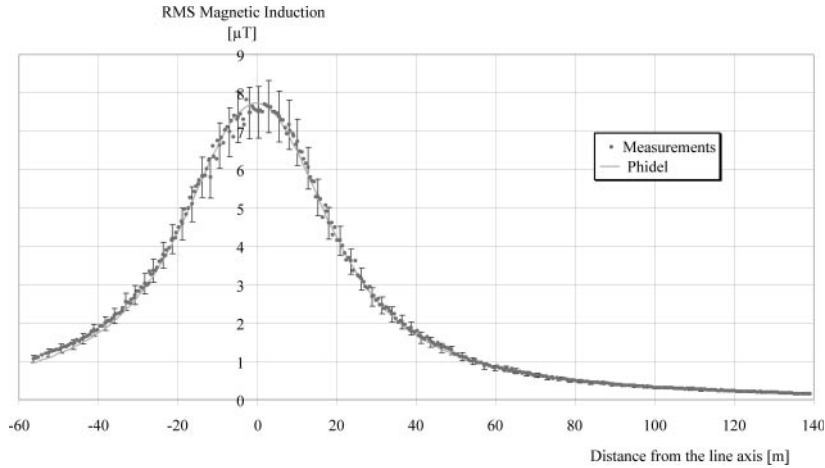
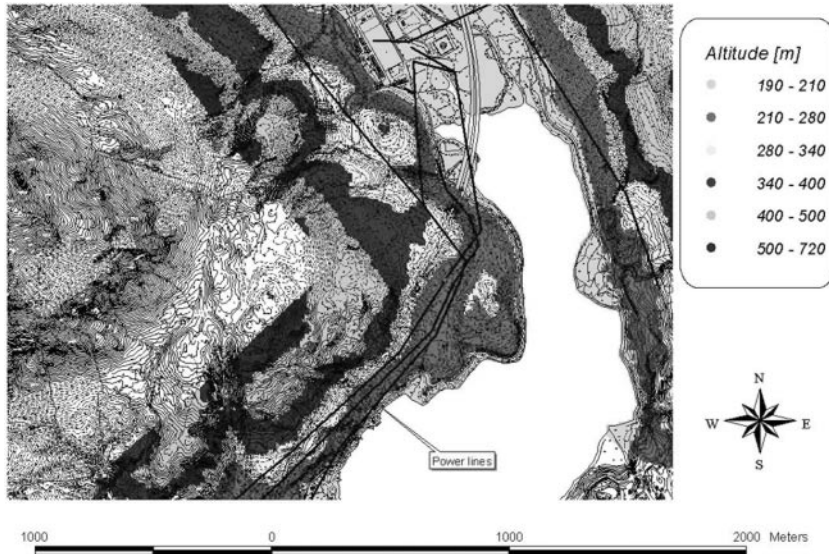Figure 7. Comparison between experimental data and software results.

Figure 8. Determination of territory orography.

and infinite, and they do not allow to consider the span form, nor the line trajectory.

The use of Phidel contributes to economising time, because it supplies the required data with no further processing to consider the angle of the trajectory path relatively to the normal 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 accordance between the measurements and the software output data, demonstrating that the data supplied by Phidel are definitely more reliable.

OROGRAPHIC EVALUATION

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

This example describes a situation with two 220 kV and one 132 kV power lines (Figure 8), starting
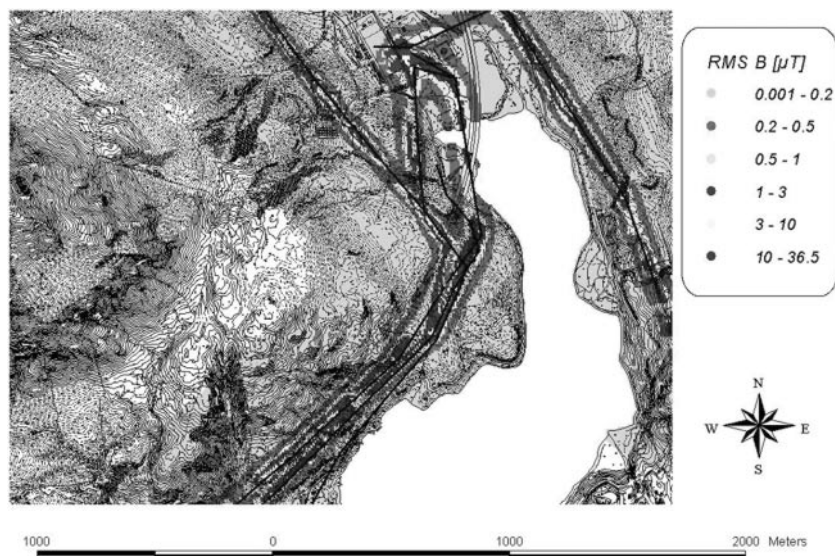
Figure 9. Calculation of magnetic induction (particular).

from the same primary transformation station (in Somplago, Italy). This was chosen for the presence of several power lines and for the particular orography (the station is set between two mountains and in front of a lake, where there are no quoted points in the digital cartography).

The evaluated points belong to a regular grid, whose extension can be later reduced following an irregular contour decided by the user, as shown in Figure 8.

The result of Phidel's orographic evaluation is shown in Figure 9: it allows to evidence the 3 μT level for the induction magnetic field at a desired height, as required by Ref. (1).

CONCLUSIONS

The necessity to calculate magnetic induction in complex power line configurations has led to the development of a new tool, called Phidel, which remarkably improves the data input, the processing and visualisation procedures, and above all allows to consider systems made up of several lines, both aerial and underground, and correctly evaluate the extension of field volumes which exceed the values specified by the current Italian laws using the only approximation of the span discretisation.

The algorithm implements the Biot–Savart law, and it is therefore conform to the Report No. CEI 211-4[6] requirements. The software supplies output data which are compatible with the GIS software used by the agency, and the batch modality allows to elaborate large amounts of data referring to complex configurations.

The implementation in PHP and through the Visual C++ programming language enables to gain in versatility, portability and efficiency, guaranteeing 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 enables the user to decide whether the law limits are respected or not.

Finally, the comparison of Phidel with the software products used in the other Regional Agencies has shown a greater consistency with the measurements and a better conformity with the data supplied by the plants owners.

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