An intelligent computing technique to estimate the magnetic field generated by overhead transmission lines using a hybrid GA-Sx algorithm


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A R T I C L E   I N F O

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A B S T R A C T

The application of certain Artificial Intelligence techniques provides an efficient solution to the problem of characterizing the magnetic field of a high voltage overhead transmission line, and is an alternative to the expensive procedure of direct measurements, which requires equipment and time, to the use of complex numerical methods of a very specific scope, or of simply obtaining a theoretical value calculated using analytical procedures which forego the quality of the solution in favor of simplifying the calculations. This paper presents an implementation based on a hybrid algorithm in which the best solutions provided by a metaheuristics (a genetic algorithm which allows working with extensions) define the initial simplex for the application of the Nelder–Mead Method, which as a local search method permits a calculation-intensive search. In order to validate the quality of the results generated by this hybrid implementation, the estimates obtained are compared with measured values and with values obtained by means of analytical procedures.

1. Introduction

Since the late 1970s, when Wertheimer and Leeper [1] suggested the existence of a connection between the presence of overhead high voltage transmission lines (OHTLs) and certain illnesses (leukemia and other types of cancer), there has been a great deal of discussion regarding the possible effects of electromagnetic fields on living beings, which in the case of transmission lines acquires an important social dimension.

The exact calculation of these electromagnetic fields requires using Maxwell’s equations. Only very simple geometries allow to calculate the magnetic field by direct integration of Maxwell’s equations.

Since they were first formulated, different methods of analysis and calculation have been developed on the basis of highly complex mathematical formulations in respect to both time and the frequency dimension. However, this scenario changed radically with the development of very powerful computers with huge calculation potential, enabling the application of numerical methods to resolve Maxwell’s equations.

Analytical methods have been applied in [2–4]. They entail two main advantages in respect to other techniques, namely they provide information regarding the parameters that affect the magnetic field generated by overhead lines and allow analyzing new configurations in a simpler manner. The multi-pole expansion is used in [2]. A procedure based in a discrete approximation of the Biot–Savart law, that takes into account the catenary effect of the conductors, with a polygonal approximation is proposed in [3]. This method has several advantages, as allows transpositions and changes in the direction. The method used in [2] has been re-formulated in [4] using double complex number, allowing the simultaneous treatment of position vectors and phasors in order to obtain exact expressions. This method is valid only for electrical lines with polygonal symmetry, but not for any configuration. The main disadvantage of analytical methods is that the calculated magnetic field value is only valid at large distances from the line compared to the distances between conductors.

Empirical methods based on procedures that characterize OHTL’s electromagnetic environment using measurements taken “on site” can be found in [5,6]. In [5] a theoretical method has been validated to calculate the magnetic field in the vicinity of OHTL using measured values and considering harmonics and unbalanced currents. In [6] the authors evaluate the European Union normative in a 400 kV substation.

These procedures result expensive in time and equipment. A disadvantage is the change in the electrical and environmental conditions during the measurement process.

Many authors have used numerical methods, as the finite element method [7], the Charge Simulation Method [8] and the Finite Difference Method [8]. The large amount of computational resources required by numerical methods do they not to be feasible for the calculation of magnetic fields produced by overhead lines in a reasonable time. Furthermore, the meshing process affects to the
quality of the solution and the execution time. These methods do not evidence the relationship between the magnetic field and the geometric and electrical parameters of the line. Furthermore, they present some disadvantages related with the meshing process, execution time, and others.

The methods without mesh avoid some of these disadvantages; i.e. in [9] the physical domain is discretized in a sparse set of points and the form functions are used to interpolate the field variables. The results are generally smooth and hence they do not need any further processing. The disadvantage is that they require a numerical integration of higher order.

The above consideration justify the need for new efficient procedures able to obtain the magnetic field at any point in space from only basic parameters such as phase currents and the position of the conductors with respect to the calculation point.

2. Preliminary considerations

Many different Artificial Intelligence (AI) techniques are used in the Electrical Engineering [10–14]. The proposed solution stems from the idea of checking the feasibility of applying certain AI techniques to the characterization of the magnetic environment of an OHTL as an alternative to the expensive procedure of direct measurements, which requires equipment and time, or of simply obtaining, by applying the analytical procedures, the calculated values needed for comparative studies exist.

At this point there exist two options: either to use this data to measure the curve. Once the function has been identified, it suffices to replace the unknown function is calculated obtaining the linear and nonlinear coefficients using available measured values that correspond to the IEEE Std 644 protocol, in order to ensure that data used in the analytical procedures to be considered, so that the empirical and theoretical data can be compared.

The procedure of choice is the empirical one; however, all the measurements required by the protocol are not always available.

For example, the least demanding protocol in respect to distance nonetheless requires a high voltage corridor that is completely clear [15]. In most rural areas this does not entail a drawback. However, it is usually in urban areas where there is a greater interest in characterizing the magnetic environment of an electric power line. Within the distance of the protocol there are often dark areas due to the presence of roads, residential areas, private properties, slopes, etc., making it difficult and in most cases impossible to obtain measured values. In these cases the measured value is substituted with a value calculated using analytical procedures.

The characterization of the magnetic environment of an OHTL is obtained with the longitudinal profile, which is composed discretely of the different cross sections defined at the points of measurement specified in the protocol. However, there are occasions in which only some measurements are available, with those that are not available corresponding to the points that are the furthest from the OHTL layout.

The approximation we are going to propose, and the algorithms that develop this approximation, comprise an alternative procedure to the use of theoretical values, which requires designing and validating a function approximator to estimate the minimum number of available measurements needed to construct the transverse and longitudinal profiles that define the magnetic environment of the selected span. For this first case study we have chosen a double structure with a Genetic Algorithm (GA) and a hybrid modified GA/simplex method.

3. Proposed approach

The approach proposed in this work consists of obtaining a function named reduced equivalent equation (REE) that generates the measured values, dependent on the distance to the estimated measurement.

The unknown function is calculated obtaining the linear and nonlinear coefficients using available measured values that correspond to the IEEE Std 644 protocol, in order to ensure that data needed for comparative studies exist.

Once the function has been identified, it suffices to replace the value at a certain distance to obtain the value of the required measurement.

After making numerous tests with different functions (polynomial, quadratic, trigonometric, exponential (1), etc), we concluded that the exponential function was the one that had the smallest accumulated error (norm) and allowed the best adjustment to measure the curve.

\[ B_m = \sum_{j=1}^{n} L_j \cdot e^{-N_{L_j} x^2} \]  

(1)

At least we need to establish a solution of commitment between the approach to obtain (the validity of the solution contributed) and to the calculation complexity of present parameters in exponential function terms. In our case, we can assure that the results are acceptable with the length of two terms.

\( L_j \) (linear coefficients) and \( N_{L_j} \) (nonlinear coefficients) are the parameters to be estimated. Variable \( x \) represents the distance at which the measurement is taken.

The identification of the linear and nonlinear coefficients of the REE must be calculated optimizing their value in order to minimize the accumulated error between the measured and estimated values.

4. Genetic algorithm

The first AI technique proposed to identify the linear and nonlinear REE coefficients is a GA. GAs are used in many applications of Electrical Engineering [16,17].
GAs are adaptive metaheuristics that are used to resolve search and optimization problems. These algorithms are based on the mechanics of natural selection and the genetics of living beings to make an initial population of points evolve successively towards better regions of the search space. Throughout the generations, the populations evolve in nature on the principles of natural selection and survival of the fittest postulated by Darwin.

This GA constitutes the principal structure of a parametric approximator which determines the value of the desired coefficients in such a way that the accumulated root mean square error (Euclidean norm) between the estimated values of the magnetic field corresponding to the field points of the defined protocol and the available measurements of said points is minimal.

The GA’s structure is shown in Fig. 2.

The algorithm’s parameters and the operator’s constants were adjusted by means of the experimental analysis of specific instances, a procedure known as OFAT (one factor at a time), which consists of observing the GA’s sensitivity when the value of one of its parameters is modified, leaving the other values constant. The final values that were adopted were computed with Matlab and are shown in Table 1.

As an example, Fig 3 shows the quality of the solution reached (fitness) through the selection of one of these critical parameters. The fitness has been assessed in terms of the convergence rate (number of generations) for different population sizes.

It is observed that for a 100 individuals population, the solution quickly reaches a convergence value which represents an excellent tradeoff between quality of the results and the computational efficiency of the algorithm.

### 5. Hybrid genetic algorithm

Due to the stochastic nature of GAs, in which the solution space is thoroughly explored, convergence is much slower than with local optimization methods. Even when a GA is in the region of the global solution, the method’s internal mechanism forces it to continue with the same dynamics, unless, for example, a decision is made to reduce the probability of mutation in the final phase of optimization.

The objective of Hybrid Genetic Algorithms (HGAs) is to reach a balance between the exploration and the speed of convergence.

### Table 1
Adjustment values of GA parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generations ((k))</td>
<td>100</td>
</tr>
<tr>
<td>Size of population (P_{ob})</td>
<td>100</td>
</tr>
<tr>
<td>Probability of cross (P_c)</td>
<td>0.80</td>
</tr>
<tr>
<td>Probability of mutation (P_m)</td>
<td>0.080</td>
</tr>
<tr>
<td>Codification</td>
<td>Binary</td>
</tr>
<tr>
<td>Length of gene</td>
<td>16 bits</td>
</tr>
<tr>
<td>Length of chromosome</td>
<td>(4 \times 16 = 64) bits</td>
</tr>
<tr>
<td>Selection operator</td>
<td>Deterministic tournament (p = 2)</td>
</tr>
<tr>
<td>Cross operator</td>
<td>Single point</td>
</tr>
<tr>
<td>Fitness function</td>
<td>Euclidean norm</td>
</tr>
<tr>
<td>Finalization criterion</td>
<td>By number of generations</td>
</tr>
</tbody>
</table>

![Fig. 2. GA flowchart.](image)

![Fig. 3. Relationship fitness/generations for several population sizes.](image)
Basically, the idea consists of combining the potential of GAs and of a second method of optimization, normally a local search method; and undoubtedly, when hybridization and metaheuristics are considered, the third element is the Nelder–Mead Method or Simplex Modified System (Sx).

The Simplex method is a sequential optimization method based on the use of a simplex, which is a geometric figure of \( n \) dimensions, defined on the basis of \( n + 1 \) vertices. Each dimension corresponds to a variable to be optimized. The Simplex method, originally introduced by Spendley et al. [18], is not based on a factorial approach, which is why it requires only a few experiments to move in the direction of the optimum. The original Simplex method has undergone modifications over the years; for example, Nelder and Mead [19] proposed a series of modifications of the basic method's rules of movement. These modifications made it possible to obtain a stationary optimum point with sufficient precision and clarity, and also allowed for a more rapid development of the simplex in the direction of the optimum, giving rise to the so-called Modified Simplex Method (Sx) or Nelder–Mead Method, where the size and form of the simplex can be altered.

Many works have demonstrated the validity of hybridation of a GA with intensive techniques [20] in general [18], and in particular with the Sx [21–23]. This hybridization permits improving performance, both in terms of computation cost and the quality of the solution, given that the global method evolves until it reaches a solution (diversification), which is later refined with the local search method (intensification).

The only problem consists in correctly selecting the optimum point of insertion of the local method, because if the GA has not yet reached an adequate region, convergence could correspond to a poor quality solution. On the other hand, if GAs are allowed to evolve too much, the potential of hybridization is not put to good use. The idea is to use the criteria of solution quality and computation cost to answer the two classic questions: When to connect them? and How to connect them?

In order to respond to these two questions and thus enable the HGA to improve both the quality of the solution obtained and its efficiency, the strategy considered in the previous section is modified and applied as shown in Fig. 4.

- Even though the values of the parameters adjusted for the GA are maintained, only three iterations are performed. Termination of these three iterations marks the point at which the local search is launched.
- Each iteration of the GA provides a solution defined by the values corresponding to the two linear coefficients and the two nonlinear ones.
- Of the three previous solutions, the one that provides greater fitness will provide the value of the linear coefficients, which are determined at that moment and thus are not subject to the subsequent refinement performed during the local search (improvement of computational efficiency).
- The Sx method is applied in a bidimensional search space and thus over a simplex defined by three vertices \((n + 1)\).
- In accordance with the rules of movement of the simplex in the Sx method, the operations selected in each iteration are applied until convergence is reached (fulfilling the stop condition).
- The final solution consists of the values of the linear coefficients \(L_1\) and \(L_2\) obtained by the GA and the values of the nonlinear coefficients \(NL_1\) and \(NL_2\) provided by the GA and refined by the Sx method (GA/Sx hybridization).

6. Validation

In order to validate the function approximator, it was applied to a set of OHTLs with the following objectives:

- To establish a procedure that would allow estimating, on the basis of a small number of available measurements, the values of the magnetic field generated by the OHTL at points where measurements cannot be taken due to accessibility problems.

![Fig. 4. Flowchart of GA/Sx hybridization.](image-url)
6.1. Line 1: 380 kV single circuit flat configuration

The first validation example (flat line) allows generalization regarding one of the most frequent cases encountered in the validation set, namely lines with symmetrical magnetic field density \( B_m(x) = B_m(-x) \) whose layout is in a clean magnetic environment (\( B_m \approx B_0 \)).

The geometric characteristics appear in Fig. 5 [10].

The theoretical values of the magnetic field generated by the flat configuration were calculated using Eq. (2). The analytical method used to calculate the theoretical values is based on the representation of the magnetic field vectors with double complex numbers [4].

\[
B = \frac{\mu_0 I \cdot s}{2 \cdot \pi \cdot R} \sqrt{\frac{3 \cdot R^2 + s^2}{R^2 - 2 \cdot R^2 \cdot s^2 \cdot \cos (2 \cdot \varphi_R + s^2)}} \tag{2}
\]

where \( B \) is the magnetic flux density (T), \( I \) the line current (balanced without higher harmonic components), \( h \) the free height, distance between the theoretical ground line and the conductor closer to it, \( s \) the horizontal distance between conductors, \( R \) the distance between the source and the field point, \( \varphi_R \) the angle of vector \( R \) in relation to the horizontal axis, \( \mu_0 \) the magnetic permeability of free space (\( 4 \pi \times 10^{-7} \text{ V s/A m} \)).

Depending on the percentage of available measurements, application of the GA function approximator generates the REE coefficient values shown in Table 2.

![Fig. 5. Flat configuration.](image)

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Euclidean norm and REE coefficients for different percentages of measurements available in Line 1.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference values</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------</td>
</tr>
<tr>
<td>100%</td>
<td>Theoretical values</td>
</tr>
<tr>
<td>87.5%</td>
<td>Measured values</td>
</tr>
<tr>
<td>75%</td>
<td></td>
</tr>
<tr>
<td>62.5%</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* In respect to measured values.

To avoid using simplified theoretical calculation procedures to obtain missing values without considering the characteristics of the OHTL environment (presence in the vicinity of other generating sources), which could provide values that greatly differ from measured ones.

To determine the minimum number of measurements needed to complete the protocol that allows characterizing the magnetic environment of the selected span.

To determine the width of the right of way to ensure, at both ends, a magnetic field value lower than a specific regulation.

To observe the behavior of the function approximator proposed for OHTLs with asymmetries located in different types of magnetic environments.

Note should be made that in all the tests carried out, the most adverse scenario has been assumed; in other words, that available measurements are the ones that are closer to the line’s main axis, even though there will be many occasions in which measurements are not available for intervals within the width of the measurement protocol [−35, 35] m, so that function approximation can be performed with greater precision.

The results obtained in 3 OHTLs (one for each configuration studied) are shown below, as an example of the lines that comprise the validation set on which our conclusions are based.

Fig. 6 shows the curves of measured and theoretical values as well as the curves of values estimated after substituting the coefficients shown in Table 2.

Fig. 6 shows that theoretical, measured and estimated values closely coincide in the central part of the transverse profile [−20, 20] m, with major discrepancies at the ends, precisely where the field value is lowest, which is why their contribution to the accumulated root mean square error is usually of minor importance.

As can be inferred from Table 2, the limit of the minimum number of available measurements in this line is 75% (generated norm lower than the theoretical norm). Thus, in the case of a flat longitudinal profile (without any difference of levels between supports), in order to comply with the number of field values needed, measurements have to be taken in just 18.75% (75 \( \times 0.25 \)) of the points contemplated in the protocol, where 0.25 is the longitudinal and transverse symmetry factor.

Application of the hybrid algorithm (GA-Sx) to available measurements (reference to calculate the Euclidean norm) produces the results shown in Table 3.

In respect to the operation of the Sx method, Table 4 shows the number and types of movements performed the simplex. Fig. 7
shows the sequence of said movements until convergence is reached following 220 iterations.

The longitudinal profile is constructed by repeating the process for all 11 transverse profiles defined in the protocol. Fig. 8 shows the longitudinal profile of the 100 meter long selected span and taking into account the catenary effect.

6.2. Line 2: 20 kV single circuit delta configuration

The second example of validation (Delta Line) allows generalization in the case of a “dirty” magnetic environment, in other words lines whose theoretical magnetic field density values at certain points substantially differ from measured values ($B_m \neq B_t$).

The geometric characteristics are shown in Fig. 9 [10].

The theoretical values of the magnetic field generated by the Delta configuration were calculated using Eq. (2). The analytical method used for the calculation of the theoretical values is based on the representation of the magnetic field vectors with double complex numbers [4].

$$B = \frac{3 \cdot \sqrt{2} \cdot \mu_0 \cdot I \cdot p}{4 \cdot \pi} \sqrt{R^4 - 2 \cdot R^2 \cdot p^2 \cdot \cos (3 \cdot \varphi_p) + p^4}$$  (3)

Depending on the percentage of available measurements, application of the GA function approximator generates the REE coefficient values shown in Table 5.

---

**Table 3**

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Euclidean norm</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>0.1869</td>
<td>–</td>
</tr>
<tr>
<td>GA</td>
<td>0.0238</td>
<td>87.27</td>
</tr>
<tr>
<td>GA/Sx</td>
<td>0.0231</td>
<td>87.64</td>
</tr>
</tbody>
</table>

**Table 4**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion</td>
<td>14</td>
</tr>
<tr>
<td>Reflection</td>
<td>142</td>
</tr>
<tr>
<td>Contraction</td>
<td>57</td>
</tr>
<tr>
<td>Degenerate contraction</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>220</td>
</tr>
</tbody>
</table>

---

Fig. 10 represents the curves of measured and theoretical values as well as the curves of values estimated after substituting the coefficients of Table 5.

Fig. 10 shows the great similarity of measured and estimated values in the transverse profile’s central area $[-20, 20]$ m. The main errors occur at both ends, precisely where the field value is
lowest, which is why their contribution to the accumulated error is usually of minor importance.

However, the theoretical values differ considerably from the estimated and measured values. The dirty magnetic field due to the presence of other generating sources in the vicinity of the OHTL is not taken into account in the theoretical calculations.

As can be inferred from Table 5, the limit of the minimum number of available measurements in this line is 50% (generated norm lower than the theoretical norm). Thus, in the case of a flat longitudinal profile (without any difference of levels between supports), in order to comply with the number of field values needed measurements have to be taken in just 12.50% (50 \times 0.25) of the points contemplated in the protocol.

Application of the hybrid algorithm (GA-Sx) to available measurements (reference to calculate the Euclidean norm) produces the results shown in Table 3.
As shown in Table 6, the proposed approximators (GA and GA/Sx) significantly improve the accumulated root mean square error or Euclidean norm.

In respect to the operation of the Sx method, Table 7 shows the number of each type of movement performed by the simplex, and Fig. 11 shows the sequence of said movements until convergence is reached following 76 iterations.

Fig. 12 shows the longitudinal profile of the selected span for a length of 100 m, taking into account the catenary effect.

6.3. Line 3: 132 kV double circuit line

The third example of validation is a double circuit line with a vertical flat configuration \((a_1 - b_1 - c_1/a_2 - b_2 - c_2)\). This configuration allows checking generalization achieved in the case of asymmetries in respect to the OY axis \((B_{m}(x) \neq B_{m}(-x))\) due to the presence of geographical features that modify the measurement level.

The geometric characteristics are shown in Fig. 13 [10].

The theoretical values of the magnetic field generated by the double circuit configuration were calculated by using Eq. (4). The analytical method used for the calculation of the theoretical values is based on the representation of the magnetic field vectors with double complex numbers [4].

\[
B = \frac{3 \cdot I \cdot \mu_0}{2 \cdot \pi} \sqrt[12]{\frac{R^8 + s^2 \cdot R^6 + 2 \cdot s^4 \cdot R^4 \cdot (\cos (2 \cdot \phi_k) - \cos (4 \cdot \phi_k)) + s^6 \cdot R^2 + s^8}{R^{12} - 2 \cdot R^8 \cdot s^6 \cdot \cos (6 \cdot \phi_k) + s^{12}}}
\]

(4)

Depending on the percentage of available measurements, application of the GA function approximator generates the REE coefficient values shown in Table 8.

Fig. 14 represents the curves of the measured and theoretical values as well as the curves corresponding to the values estimated after substituting the coefficients of Table 8.

Fig. 14 shows the great similarity of theoretical, measured and estimated values in the entire transverse profile \([-35, 35]\) m, with the exception of the curve obtained for 50% of the available measurements.
In consequence, from Table 8 we can conclude that the limit of the minimum number of available measurements in this OHTL is 62.5% (generated norm lower than the theoretical norm). Thus, in the case of a flat longitudinal profile (without any difference of levels between supports) as shown in Fig. 14, in order to comply with the number of field values needed measurements have to be taken in just 16.13% (62.5 × 0.25) of the points contemplated in the protocol.

Application of the hybrid algorithm (GA-Sx) to available measurements (reference to calculate the Euclidean norm) produces the results shown in Table 9.

Table 10 shows the number of each type of movement performed by the simplex and Fig. 15 shows the sequence of execution of said movements until reaching convergence following 108 iterations.

The longitudinal profile is constructed by repeating the process for each one of the 11 transverse profiles defined in the protocol. Fig. 16 shows the longitudinal profile of the selected span for a length of 100 m, taking into account the catenary effect.

7. Conclusions

The paper presents a new and very efficient procedure based on IA techniques that allows the characterization of the magnetic environment of OHTLs.

In order to validate the results, measured values obtained following the IEEE Std 644 protocol and theoretical values obtained by means of analytical procedures were used.
Table 8
Euclidean norm and REE coefficients for the different percentages of measurements available in Line 3.

<table>
<thead>
<tr>
<th>Reference values</th>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$NL_1$</th>
<th>$NL_2$</th>
<th>Euclidean norm*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical values</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.1974</td>
</tr>
<tr>
<td>Measured values available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td>1.0461</td>
<td>0.6365</td>
<td>0.0073</td>
<td>0.0010</td>
<td>0.0633</td>
</tr>
<tr>
<td>87.5%</td>
<td>0.9984</td>
<td>0.6863</td>
<td>0.0078</td>
<td>0.0011</td>
<td>0.0643</td>
</tr>
<tr>
<td>75%</td>
<td>0.9167</td>
<td>0.7694</td>
<td>0.0083</td>
<td>0.0013</td>
<td>0.0840</td>
</tr>
<tr>
<td>62.5%</td>
<td>1.0594</td>
<td>0.6250</td>
<td>0.0074</td>
<td>0.0008</td>
<td>0.0970</td>
</tr>
<tr>
<td>50%</td>
<td>0.0000</td>
<td>1.6787</td>
<td>0.1782</td>
<td>0.0041</td>
<td>0.5679</td>
</tr>
</tbody>
</table>

* In respect to measured values.

Table 9
Values of the Euclidean norm and the improvement achieved in respect to the theoretical value in Line 3.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Euclidean norm</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>0.1964</td>
<td>–</td>
</tr>
<tr>
<td>GA</td>
<td>0.0633</td>
<td>67.77</td>
</tr>
<tr>
<td>GA/Sx</td>
<td>0.0633</td>
<td>67.77</td>
</tr>
</tbody>
</table>

Table 10
Simplex movements for Line 3.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion</td>
<td>25</td>
</tr>
<tr>
<td>Reflection</td>
<td>56</td>
</tr>
<tr>
<td>Contraction</td>
<td>26</td>
</tr>
<tr>
<td>Degenerate contraction</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>108</td>
</tr>
</tbody>
</table>

Fig. 14. Line 3, approaches to measurement curves.

Fig. 15. Sequence of simplex movements for Line 3.
Obtaining estimated values by means of parametric approximators whose internal structures correspond to a metaheuristic (GA) and to a hybrid algorithm (GA-Sx) enables achieving balanced solutions in respect to required quality and computational cost and complexity.

The numerical solutions obtained reveal considerable improvement in the quality of the solutions achieved in the estimations made in the validation process.

In the implementation by means of a genetic algorithm, estimating unknown values of the magnetic field on the basis of available values enables us to have values that correspond to a quality solution, and also to know the minimum number of measurements needed to have a complete profile that satisfies specific quality conditions. The model allows easy adaptability to geometric and electric modifications in the lines, both transitory and permanent.

The main contribution of the paper the verification that this solution entails an improvement in respect to the solution obtained with analytical procedures.

In the implementation by means of the Hybrid GA/Sx Algorithm, even though the quality of the solution achieved is not improved, the main contribution is the improvement of the time needed by the CPU to achieve solutions of a quality similar to that of solutions obtained with the GA.

The limitations of this study are related to the complex configurations of high-voltage overhead lines due to the large number of parameters involved.

Future research should address the design of adaptive GA configurations to increase the convergence speed, and allow the generalization of the problem to more complex OTL configurations.

**References**