Active shielding for power-frequency magnetic field reduction using genetic algorithms optimisation

S. Celozzi and F. Garzia

Abstract: An active shielding technique is presented for the reduction of the magnetic field generated by power lines based on the use of active conductors whose positions and currents are found optimally using a genetic algorithm technique. Significant reductions of magnetic flux density into any desired target area are obtained at limited cost.

1 Introduction

Increasing concern about possible adverse health effects of low-intensity power-frequency magnetic fields, in some way confirmed by the International Agency for Research on Cancer (IARC) [1], yields to the conclusion that a reduction of the magnetic field due to power lines has to be pursued, especially if costs can be minimised at the design stage or low-cost remedies can be applied in existing installations. It is well known that passive shields, either ferromagnetic or not, are not effective enough at low frequencies. In the past, attempts have been made concerning active shields [2, 3], especially loops, to be lain in close proximity of the area where a mitigation is sought for; however, it has been demonstrated that such a mitigation technique is not sufficient in most cases.

In this paper a technique is presented for the management of the magnetic field arising from either overhead lines or buried cables, based on the use of active conductors for compensation. The optimal choice of currents to be driven in the compensation wires is obtained by means of a genetic algorithm, which compares favourably with deterministic algorithms in terms of accuracy and computational costs. The main idea [4] for high-voltage overhead lines consists basically in driving the guard wire, and eventually other new underground wires to be installed, with a current capable of generating a magnetic field almost opposite to that due to the source, in a given region. Additional, buried cables should be used in the case of three-phase cable sources. The source configuration considered is schematically shown in Fig. 1. Balanced or unbalanced three-phase systems may be dealt with as well.

The main novelties in the proposed approach are that the currents in the active wires (installed to achieve the mitigation) are independent of each other because they return through the earth; the guard-wire is used as one of the active wires; and their position and current are optimised genetically. As to the first aspect, losses associated with the return current may be tolerated because generally the mitigation has to be achieved only for short lenghts, i.e. where human exposure is planned.

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The authors are with the Department of Electrical Engineering, University of Rome “La Sapienza”, Via Eudossiana, 18, Rome 00184, Italy

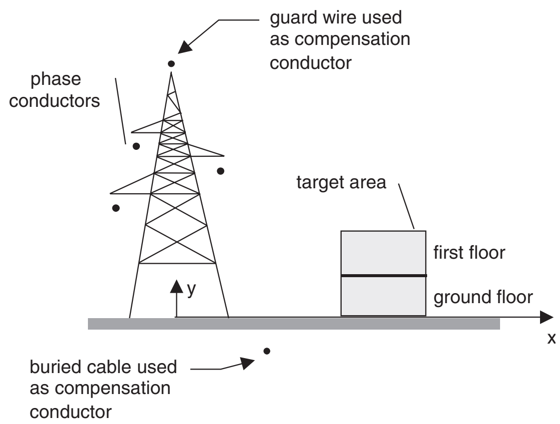

Fig. 1 *Overhead three-phase line and area where a mitigation is sought through two active wires*

2 Mitigation strategy and equations

Often, the mitigation is required on one side of the line only, at distances between 10 and 50 metres; without loss of generality, in the following the magnetic flux density is assumed to be lying in a plane transverse to the line direction, denoted as the z-axis. In fact, an adequate choice of the equivalent height of the line conductors will account for their sags with good accuracy [5] and a considerable simplification in the formulation is obtained. Extension to the general case is straightforward. As a measure of human exposure conditions, until other quantities are identified, the RMS value of the magnetic flux density is used, as generally recognised and agreed.

The goal of the mitigation is the determination of currents to be driven in additional wires, whose position is still to be determined, in such a way that a reduction of the magnetic flux density is observed in the area of interest. Unfortunately, after the mitigation is achieved, it may happen that on the opposite side with respect to the line, an increase in the magnetic flux density is observed. To prevent this, a passive, partial shield may be considered for altering the field distribution on one side without affecting the other side [4]. The return of both the currents may be through the ground, since generally the compensation is needed for a short length of the line and power losses may be tolerated. Thus, the following inequality has to be solved:

$$B(x,\ y) = \sqrt{B_x^2 + B_y^2} \leq B_{thres} \quad x \in [x_1, x_2],\ y \in [y_1,\ y_2] \tag{1}$$

where B is the total field (RMS value) due to the source conductors and to the compensation wires, B_{thres} is the threshold value of the magnetic flux density and the target area is defined by the two intervals along x- and y-axes (due to multiple-floor buildings, for instance), as shown in Fig. 2.

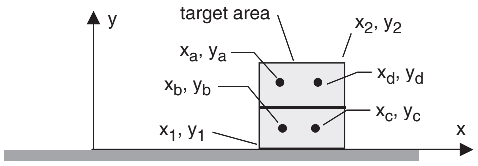

Fig. 2 *Target area and approximation points*

The optimal solution may be sought by introducing a global parameter to be minimised as

$$\Psi(x_1, x_2, y_1, y_2) = \int_{x_1}^{x_2} \int_{y_1}^{y_2} B(x, y) dx\, dy \qquad (2)$$

Ψ is not a flux, but represents the integral of the modulus of the vector magnetic flux density over the surface of interest. Under the foregoing hypotheses, the integral (2) can be approximated as [6]

$$\Psi \cong \frac{\Delta x \cdot \Delta y}{4} \sum_{k=a}^{d} B_k(x_k, y_k) \qquad (3)$$

where $\Delta x = x_2 - x_1$, $\Delta y = y_2 - y_1$, $x_{av} = \Delta x/2$, $y_{av} = \Delta y/2$ and the four discrete points are

$$x_a = x_{av} - \frac{\Delta x}{2\sqrt{3}}, \; y_a = y_{av} + \frac{\Delta y}{2\sqrt{3}} \qquad (4a)$$

$$x_b = x_a, \; y_b = y_{av} - \frac{\Delta y}{2\sqrt{3}} \qquad (4b)$$

$$x_c = x_{av} + \frac{\Delta x}{2\sqrt{3}}, \; y_c = y_b \qquad (4c)$$

$$x_d = x_c, \; y_d = y_a \qquad (4d)$$

3 Genetic algorithms and optimal design

Unfortunately the problem considered is not linear since the vector of the magnetic flux density B has a linear dependence on the current but a nonlinear dependence on the distance R that is also a parameter to be optimised, and for this reason linear methods such as the standard Simplex are not suitable for our purpose, while genetic algorithms (GAs) find an optimal application. Genetic algorithms are wide-ranging numerical optimisation methods, based on the use of natural processes of evolution and genetic recombination [7–10]. Thanks to their versatility, they can be applied in many fields, particularly applications in electromagnetic optimisation problems [11–18]. GAs are particularly useful when the goal is to find an approximate global minimum in a high-dimension, multimodal function domain in a near-optimal manner. The algorithms encode each parameter of the problem to be optimised into a proper sequence (where the alphabet used is generally binary) called a gene, and combine the different genes to constitute a chromosome. A proper set of chromosomes, called a population, undergoes the darwinian processes of natural selection, mating and mutation, creating new generations until it reaches the final optimal solution.

3.1 Features of the genetic algorithm

GA optimisers, therefore, operate according to the following nine points:

- encoding the solution parameters as genes
- creation of chromosomes as strings of genes
- initialisation of a starting population
- evaluation and assignment of fitness values to the individuals of the population
- reproduction by means of fitness-weighted selection of individuals belonging to the population
- recombination to produce recombined members
- mutation on the recombined members to produce the members of next generation
- evaluation and assignment of fitness values to individuals of next generation
- convergence check

The flow-chart of the GA operative process is schematised in Fig. 3. The coding is a mapping from the parameter space to the chromosome space and it transforms the set of parameters, generally composed of real numbers, into finite-length strings. The parameters are coded into genes of the chromosome that allow the GA to evolve independently of the parameters themselves and therefore of the solution space. If g_i is the ith coded gene representing the ith parameter of the N solution parameters, encoded by means of M_i bits b, its structure is

$$g_i = [b_1 b_2 b_3 \ldots\ldots b_{Mi-1} b_{Mi}] \qquad (5)$$

and the general chromosome c shows the following structure:

$$c = [g_1 g_2 g_3 \ldots\ldots g_{N-1} g_N] = [b_1 b_2 b_3 \ldots\ldots b_{M-1} b_M] \quad (6)$$

M being the sum of the bits that compose each gene, that is $M = M_1 + M_2 + + M_{N-1} + M_N$. Once created, the number of chromosomes has to be chosen. It strongly affects the efficiency of the algorithm in finding the optimal solution: a high number provides a better sampling of the solution space but increases the computing costs. In this problem a good compromise was obtained by means of the number of chromosomes varying between 5 and 10 times the number of bits in a chromosomes even if it is often sufficient to use a population of 40–100 chromosomes without regard for the length of the chromosome itself. The initial population can be chosen randomly or it can be properly biased according to specific features of the problem.

The fitness function (also named cost function or object function) provides a measure of the goodness of a given chromosome and therefore the goodness of an individual within a population. Since the fitness function acts on the parameters themselves, it is necessary to decode the genes comprising a given chromosome to calculate the fitness function of a certain individual of the population.

Reproduction takes place utilising a proper selection strategy that uses the fitness function to choose a certain number of good candidates. One of the easiest reproduction processes used in genetic algorithms is represented by the roulette wheel. It consists in assigning each individual of the population a portion of the wheel that is proportional to its fitness, expressed as a percentage. For this reason the roulette wheel is divided into percentage intervals (the total of the wheel corresponding to 100%) and obviously no zero is present [7]. The larger the space assigned on the wheel to each individual, the higher is the probability of selection at every wheel tournament. The tournament process is

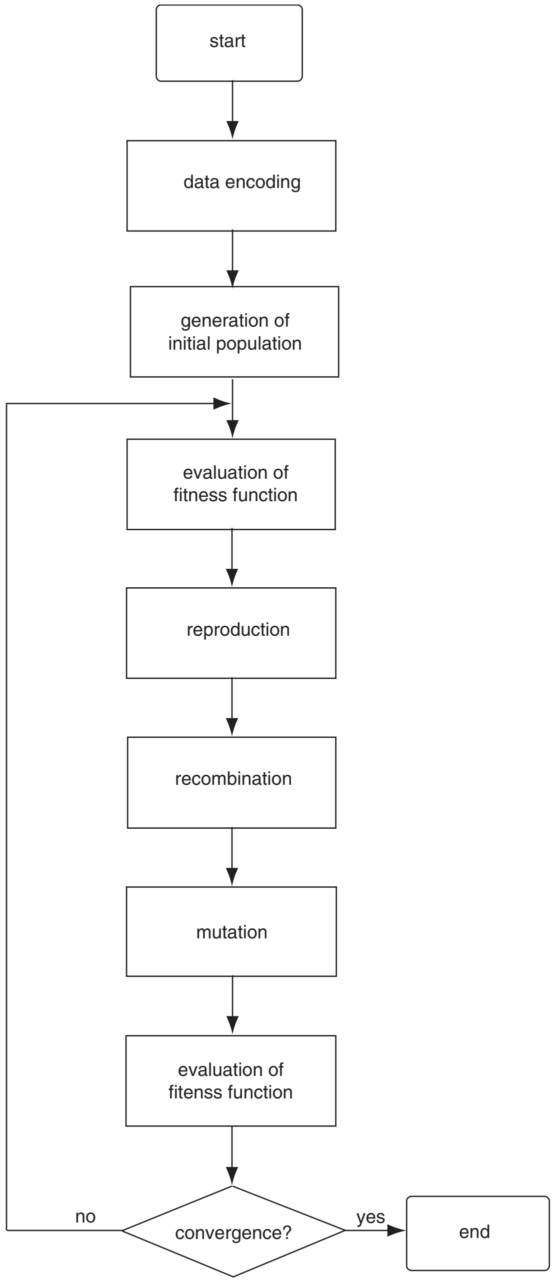

Fig. 3 *Flow-chart of the considered genetic algorithm*

repeated until a reproduced population of N individuals is formed.

The recombination process selects at random two individuals of the reproduced population, called *parents*, crossing them to generate two new individuals called *children*. The simplest technique is represented by the single-point crossover where, if the crossover probability overcome a fixed threshold, a random location in the parent's chromosome is selected and the portion of the chromosome preceding the selected point is copied from parent A to child A, and from parent B to child B, while the portion of chromosome of parent A following the random selected point is placed in the corresponding positions in child B, and *vice versa* for the remaining portion of parent B chromosome. If we denote with c_p^A and c_p^B the chromosomes of parents A and B, respectively, and if R is the random location

$$c_p^A = [b_1^A b_2^A b_3^A \ldots b_{R-1}^A | b_R^A \ldots . b_{M-1}^A b_M^A] \tag{7a}$$

$$c_p^B = [b_1^B b_2^B b_3^B \ldots b_{R-1}^B | b_R^B \ldots . b_{M-1}^B b_M^B] \tag{7b}$$

their children c_c^A and c_c^B, generated by the crossover, are

$$c_c^A = [b_1^A b_2^A b_3^A \ldots b_{R-1}^A | b_R^B \ldots . b_{M-1}^B b_M^B] \tag{8a}$$

$$c_c^B = [b_1^B b_2^B b_3^B \ldots b_{R-1}^B | b_R^A \ldots . b_{M-1}^A b_M^A] \tag{8b}$$

If the crossover probability is below a fixed threshold, the whole chromosome of parent A is copied into child A, and the same happens for parent B and child B. The crossover is useful in rearranging genes to produce better combinations of them and therefore more fit individuals. The best results have been obtained by means of a probability varying between 0.6 and 0.8 in the recombination process. The indicated values of crossover probability are the most frequently recommended in the literature of genetic algorithms [5, 7, 16] and have also shown validity in the problem considered.

The mutation is used to survey parts of the solution space that are not represented by the current population. If the mutation probability overcomes a fixed threshold, an element in the string composing the chromosome is chosen at random and it is changed from 1 to 0 or *vice versa*, depending of its initial value. To obtain good results it has been shown [7] that mutations must occur with a low probability varying between 0.01 and 0.1 and the problem under analysis confirmed this general result.

The converge check used as the stopping criterion is the achievement of the goal in terms of magnetic field level and Ψ.

3.2 Algorithm implementation and coding

Due to the features of the problem the physical controllable parameters are: the position of the underground cable, its current and the current carried by the guardwire. It has been shown [4] that in a three-phase line carrying a balanced system of currents, the maximum RMS value of the current carried by both the underground cable and the guardwire to attain good reduction results is generally less than the 30% of the phasecurrents: this is useful information to set some limits over the RMS value assumed by the current that can be expressed in term of a ratio with respect to the RMS value of the power-line current.

These considerations lead to the following six solution parameters: x- and y-co-ordinates of the underground cable, current driven in the underground cable (RMS value in % or per unit of current carried by the line, and phase), and the current driven in the guard-wire (RMS value in % or per unit of current carried by the line, and phase). The variability of the parameters indicated and the relative accuracy necessary to represent them in terms of binary strings is a critical issue in the implementation of the genetic algorithm.

Since the magnetic field values generated by power lines are generally $> 0.4\,\mu T$ up to distances of some tens of metres from their vertical axis, the x-co-ordinate of the underground cable has been allowed to vary between -63 and $+64$ m from the vertical axis, with a resolution of 1 m: this corresponds to using a seven bit gene which allows representation of 128 numbers.

For practical reasons it is not easy to bury the underground cable at a depth greater than 3 m below ground level and for this motivation the gene related to its y-co-ordinate has been represented by means of five bits, which allows representation of 32 numbers and corresponds to numbers between 0 and 3.1 m with a resolution equal to 0.1 m. As to the ratio between the RMS value of the current carried by the underground cable and the RMS value of the current carried by each wire of the three phase line, five bits have been chosen to represent 32 numbers which

Table 1: Description of genes used in the problem

Gene	Description	Variability range	Resolution	Number of bits
1	*x*-co-ordinate of underground cable	$-63 \div 64$	1	7
2	*y*-co-ordinate of underground cable	$0 \div 3.1$	0.1	5
3	ratio between RMS value of current carried by underground cable and RMS value of current carried by one line of three-phase line	$0 \div 0.31$	0.01	5
4	phase of current carried by underground cable	$0 \div 360$	1	9
5	ratio between RMS value of current carried by guard wire and RMS value of current carried by one line of three-phase line	$0 \div 0.31$	0.01	5
6	phase of current carried by guard wire	$0 \div 360$	1	9

correspond to the numbers between 0 and 0.31 with a resolution equal to 0.01 (1% steps).

The phase of the current may vary between 0 and 360°: nine bits have been considered with a resolution of about 1°. The same considerations apply to the RMS value and phase of the current in the underground cable which are equal to the current of the guardwire and six genes are therefore used to encode the control parameters and generate the basic chromosome string, whose total length is 40 bits. The gene's features are summarised in Table 1.

The fitness function is represented by the percentage difference between the global parameter Ψ, expressed by (2) and (3), in the presence of compensating currents and in their absence. The adopted fitness function yields to positive values if the compensating configuration related to the chromosome considered reduces the initial B field while it provides negative values if the opposite situation takes place. Once the population is recombined and mutated, the fitness function of the population is again calculated according to the same criteria illustrated, considering only fitting individuals. The convergence test is made, controlling whether the difference between the mean value of fitness functions of valid individuals belonging to the actual generation and the mean values of the last N_G generations are smaller than a certain percentage value p_{stop}. Good results and rapid convergence are obtained with populations composed by 40–50 individuals, with convergence test parameters N_G and p_{stop} equal to 20 and 0.1, respectively.

To assess whether the guard wire is sufficient for mitigation purposes, a specific analysis is conducted on the results achievable through a guard-wire system, without the additional compensation currents. In this case, as shown in the following Section, results are not always satisfactory.

Table 2: Geometrical arrangement of power line

Wire	X [m]	Y [m]	Current [A]
#1	−3	30	$900\angle^{\circ}$
#2	0	30	$900\angle -120^{\circ}$
#3	3	30	$900\angle -240^{\circ}$
#4 (guard wire)	0	33	to be optimised

4 Examples and case discussion

We illustrate only new results rather than repeat concepts and considerations about improvements in speed and accuracy of GAs compared with other methods, which can be found in [7, 18]. Attention is focused on a fixed power-line geometry and various situations for the target area have been considered to show the capabilities of the proposed procedure. The geometrical arrangement of the power line is summarised in Table 2.

A target area whose height and width are equal to 10 m has been considered. The distance from power line to target area has been varied and the magnetic field reduction optimised by the GA using only the guard wire (one-wire system) and both the guardwire and underground cable (two-wire system). The results are reported in Table 3 and are partially shown in Figs. 4 and 5. A number of

Table 3: Different situations, characterised by variable distance between power line and shielded zone optimised by GA and related results

Left side of shielded zone [m]	Right side of shielded zone [m]	Mean magnetic flux density, without compensation, in target area [T]	Guard-wire reduction		Guard wire+underground cable reduction				
			Optimised current in guard wire [A]	Magnetic flux-density reduction with compensation [%]	Optimised current in guard wire [A]	Optimised horizontal position of underground cable [m]	Optimised vertical position of underground cable [m]	Optimised current in guard wire [A]	Magnetic flux-density reduction with compensation [%]
0	+10	$1.50 \times 10{-}6$	$45\angle 346^{\circ}$	2.40	$27\angle 5^{\circ}$	−40	−1.6	$279\angle 152^{\circ}$	67.96
+10	+20	$1.15 \times 10{-}6$	$99\angle 333^{\circ}$	16.11	$153\angle 335^{\circ}$	−22	−1.1	$180\angle 152^{\circ}$	80.78
+20	+30	$7.83 \times 10{-}7$	$108\angle 332^{\circ}$	32.39	$144\angle 329^{\circ}$	+2	−2.5	$63\angle 143^{\circ}$	92.10
+30	+40	$5.27 \times 10{-}7$	$99\angle 330^{\circ}$	45.54	$153\angle 329^{\circ}$	−33	−3.1	$126\angle 147^{\circ}$	93.19

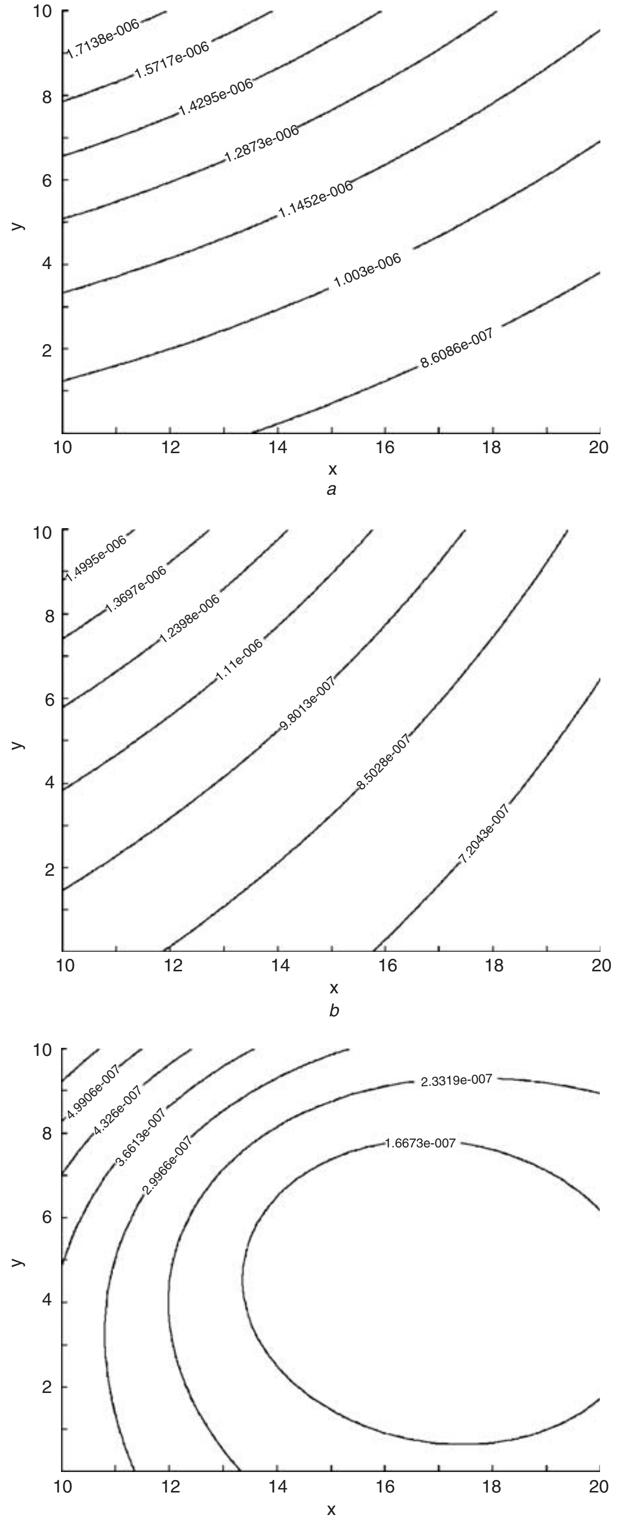

Fig. 4 *Magnetic flux density T in section considered (height = 10 m) positioned between +10 and +20 m with respect to power line vertical axes for different situations*

a Magnetic field in absence of compensation (mean magnetic flux density = 1.15×10^{-6} T

b Guard-wire compensation: magnetic flux density in presence of compensation current equal to $99\angle 333°$. A in guard wire positioned in (0,33). Mean magnetic flux density is 16.11% lower than in uncompensated situation

c Guard-wire + underground cable compensation: magnetic field in presence of compensation current equal to $153\angle 335°$. A in guard wire positioned in (0,33) and compensation current equal to $180\angle 152°$. A in underground cable positioned in (−22,−1.1). Mean magnetic flux density is 80.78% lower than uncompensated situation

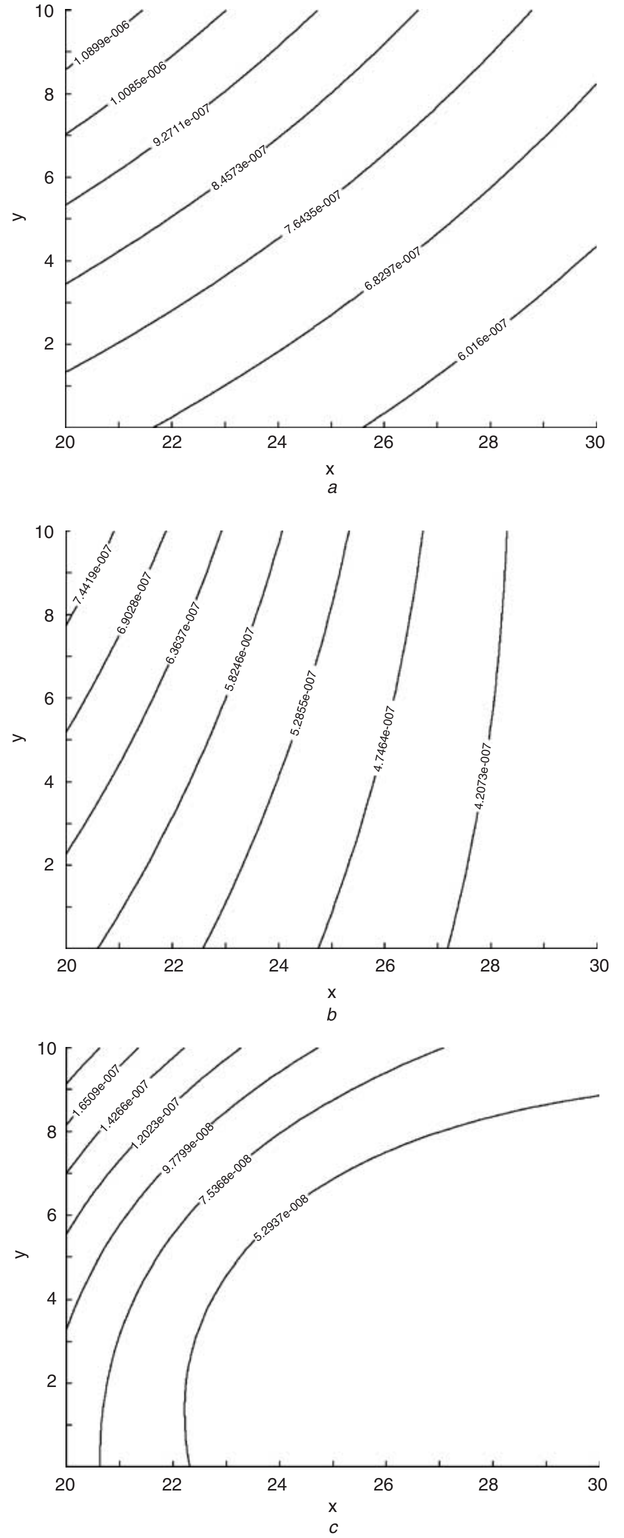

Fig. 5 *Magnetic flux density T in section considered (height = 10 m) positioned between +20 and +30 m with respect to power line vertical axes for different situations*

a Magnetic field in absence of compensation (mean magnetic flux density = 7.83×10^{-7} T)

b Guard-wire compensation: magnetic flux density in presence of compensation current equal to $108\angle 332°$. A in guard wire positioned in (0,33). Mean magnetic flux density is 32.39% lower than uncompensated situation

c Guard-wire + underground cable compensation: magnetic field in presence of compensation current equal to $144\angle 329°$. A in guard wire positioned in (0,33) and compensation current equal to $63\angle 143°$. A in underground cable positioned in (+2,−2.5). Mean magnetic flux density is 92.10% lower than uncompensated situation

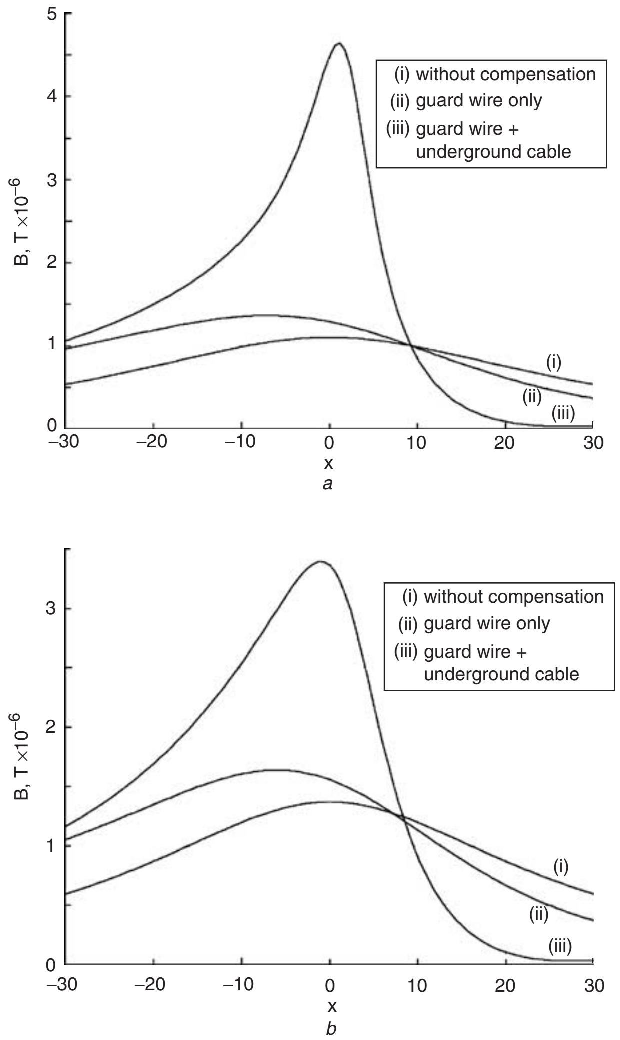

Fig. 6 *Magnetic flux density T (related to optimisation of target area positioned between +10 and +20 m) at given height H*
a $H = 1$ m
b $H = 4$ m

configurations have been analysed and only some significant examples are reported. The GA has obviously calculated different solutions for each geometry considered, but only the solution characterised by the higher percentage of reduction in magnetic flux density has been reported for each case.

Several considerations can be inferred analysing the results. The first is that the proposed compensation method ensures significant reduction of the mean magnetic flux density of 70–90%. The second is that the underground cable is always placed on the same side of the power line with respect to the target area. The position of the underground cable varies obviously with the distance between the power line and target area. The third consideration is that the compensated magnetic flux-density distribution inside the target area tends to assume a radial symmetry with respect to the approximate centre of the area considered instead of a radial symmetry with respect to the power line. Since the mitigation system is based on the installation of an underground cable where a significant compensation current may flow, the magnetic flux density is expected to assume noteworthy values in its proximity. In Fig. 6, the magnetic flux density generated by the source, by the one-wire system and by the two-wire one, is shown between −30 m and +30 m, at a height of 1 and 4 m. The situation is related to the optimisation of a target area positioned between +20 and +30 m. The two-wire system ensures a higher reduction in the target area but it also generates an increase in field in its proximity. The peak could eventually be reduced using another kind of shielding [4], but this is beyond the scope of this paper.

To verify the validity of the proposed method, different power-line geometries and different target-area configurations were optimised by the GA, generally obtaining a mean magnetic flux density reduction greater than 50%.

5 Conclusions

A new active shielding technique for the power-frequency magnetic field reduction using genetic-algorithm optimisation has been presented. It is capable of operating on any kind of geometrical arrangement of power lines and target area, guaranteeing considerable mean magnetic flux density reductions.

The use of GA techniques on this kind of problem ensures finding, always and efficiently, quasioptimal solutions that would otherwise be difficult to find due to the number of parameters involved in the optimisation problem.

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