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Optimal statistical calculation of power cables disposition in tunnels, for reducing magnetic fields and costs

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Abstract

The allocation of electric power transmission lines in tunnels is a common practice in several applications, like underground lines in urban areas, connections of cables to substations, mining and railway systems. Construction of tunnels requires difficult and costly works. Besides, limitations of external and internal magnetic fields generated by the currents in the cables of the tunnel are needed. The present paper proposes and analyzes different statistical methods for calculation of optimal dispositions of cables and tunnel dimensions for reducing magnetic field and costs, for time varying currents in the cables. The implementation of these methods to a four-circuit real case probes their effectiveness.

Keywords: Distribution grids; Magnetic fields; Optimization; Phase arrangement; Tunnels; Transmission lines; Underground cables

1 Introduction

Power cables are widely used to transmit energy in multiple applications. Usually, power plants, mining and railway facilities contain installations of power cables. Besides, high voltages underground power lines are usual in urban areas, where the use of land or environmental reasons makes preferable using underground cables instead of overhead lines. As all electrical installations, underground cables produce magnetic fields, which can be higher than in the case of overhead lines, due to the lower distance between cables and persons. For the sake of preserving health of public, the magnetic fields generated must be restricted. Generally, two kinds of limits are specified, for the general public and for the occupational professionals.

For the general public, the International Commission on Non-Ionizing Radiation Protection (ICNRP) recommended maximum value of magnetic field as 200 μT [1]. This relatively large limit has been reduced significantly by several national and regional legislations. Some states of USA have settled lower values of magnetic field limits, as in Florida (15 μT for up to 230 kV and 20 μT in higher voltages) and New York (20 μT) [2]. The EU set a recommendation of 100 μT. However, in some European countries stronger limits have been imposed [3]. In Italy, the maximum limits are 3 or 10 μT for new and existing facilities, respectively; in Slovenia and Flanders, northern region of Belgium, 10 μT; in Russia a maximum limit of 5 μT was settled for living quarters, and Switzerland established the strongest limit of 1 μT [4,5]. For occupational public, larger limits are tolerated. ICNRP specified the limit of 1000 μT. The EU set a recommendation of 1000 μT[6] and this limit is respected in most of the European countries. Some studies have focused on the problem of the exposure of workers to magnetic fields. In [7], exposures of overhead line workers and cable splicers during various works near energized conductors are assessed. In [8], the situation of research about occupational exposure to electric magnetic fields is identified. In [9], magnetic field measurements in indoor power distribution substations are shown and analyzed.

There is an increasing interest in minimization of magnetic fields generated by cables. In [10], possible techniques for reduction of magnetic field in transmission lines are summarized, based on the revision and discussion of more than 140 papers. Several calculation methods of optimal configurations of underground cables for reducing magnetic field are present in literature. In [11], an algorithm to obtain the optimal arrangement of an unbalance loaded multi-circuit underground cable system, from specified locations of cables, is shown. The authors of [12] search the reduction of magnetic fields, for arrangements of 2, 3 and 4 three-phase systems in a measurement plane 1 m above ground. The optimal phase arrangement is to obtain by interchanging the currents between determine available positions. In [13], a genetic algorithm is used to obtain the optimal configuration, also from fixed selected positions. In [14–16], several shielding solutions are presented, assuming as known the dispositions of underground cables. In [17], the cost of the disposition is introduced, in order to calculate the optimal position of cables. In this algorithm, all continuous variables are used, calculating optimal geometry of cables and phase arrangement of currents in one unique step. Then, the algorithm obtains the optimal arrangement of cables, for minimizing construction cost and limiting the maximum magnetic field for general public.

The study of magnetic fields generated for cables in tunnels is less addressed in the literature. However, the installations of cables in tunnels are very useful in many cases. In [18], the authors described the first 400 kV underground transmission line project, with cables located in a tunnel of Spain. In [19], the design and construction of the Mexican largest 400 kV transmission network in tunnel is presented. The authors of [20] presented applications of Gas Insulated Lines (GIL) in tunnels for common corridors and between neighboring countries sharing other infrastructures. The magnetic field generated by a real case of GIL is shown in the study, too. In [21], the technology and some feasibility studies of the still emerging technology of High Temperature Superconductive cables are presented, for transmission of huge quantity of electrical power. There, a triaxial cable, with the three electrical phases concentrically assembled around a common central core, is proposed. This design provides a total magnetic field compensation and almost zero electromagnetic emissions, for balanced currents. Several studies have addressed the calculation of the ampacity in tunnel (as examples, [22–24]), however the optimal calculation of the disposition of the cables inside the tunnels is still an open field of research, mainly when considering the expected variation of electrical currents.

In general, optimal cable arrangements are calculated assuming fixed currents. However, usually in real applications, the electrical currents in cables are not constant, but time varying. Consequently, this stochastic nature of the currents of the cables should be taken into account to attain an optimal design. In [25], multiple-circuit underground cable feeders allocated in a tunnel with randomly changing loads are analyzed. A normal distribution is considered for the load current on all feeder circuits. The optimal disposition of cable bundles and phases from fixed selected positions is obtained using a genetic algorithm. The authors conclude that this statistical approach provide better arrangements, generating less magnetic field values than considering only a deterministic value of current.

In the present paper, new algorithms are proposed and analyzed to obtain optimal disposition of cables and dimensions of tunnels, minimizing construction costs and magnetic field for both general and occupational public. Time changing currents are considered, resulting in a so-called statistical approach. Real data from a system of four three-phase single-core cables are used in the study. Results show that the proposed statistical approach provides cheaper solutions and with lower generated magnetic field than conventional methods.

2 The optimization problems

In the present work, the cables are arranged in four-3-phase trefoil cable bundles, selected for tunnel installations. The calculation considers: construction cost, magnetic field limits, geometrical constraints and time-varying currents flowing through the 4 circuits. The tunnel has rectangular section, with two circuits allocated in each side wall of the tunnel. Two magnetic field limits are considered:

- In a horizontal plane, one meter above the ground, to limit the exposure to magnetic field of general public.
- Inside the tunnel, providing a corridor for maintenance works for occupational professionals.

In the present case, 4 cable bundles are allocated in the tunnel. Its generalization to some other number of circuits or some other geometry in the tunnel can be easily achieved. Following, the three alternative optimization problems used in this work are described.

2.1 Calculation of the optimal geometry for four-cables bundles in a tunnel, for specified currents

In the first optimization problem, optimal coordinates for the cable bundles and the geometry of the tunnel are calculated, minimizing construction costs and assuring magnetic field constraints for both general and occupational exposures. The proposed optimization problem assembles the minimization of tunnel construction and cable installation costs in a single formulation. For given specified currents in the cables and specified magnetic field limits in the two measurement areas, the proposed optimization problem is summarized in Eqs. (1)–(17).

$$\min \left[2(c_{VarGal} + c_x)(x_{lateral} + d_{wall}) + c_y(h_{gal} - y_{\sup gal}) + 2c_{vol}(x_{lateral} + d_{wall})(h_{gal} - y_{\sup gal}) - c_p(t_1 + t_2)\right] \quad (1)$$

s.t.

$$b_x^i = \frac{\mu_0}{2\pi}\left|\left(I_{1a}\frac{y_{1a}-Y_c^i}{(X_c^i-x_{1a})^2+(Y_c^i-y_{1a})^2}+I_{1b}\frac{y_{1b}-Y_c^i}{(X_c^i-x_{1b})^2+(Y_c^i-y_{1b})^2}+I_{1c}\cdot\frac{y_{1c}-Y_c^i}{(X_c^i-x_{1c})^2+(Y_c^i-y_{1c})^2}+\ldots+I_{4a}\frac{y_{4a}-Y_c^i}{(X_c^i-x_{4a})^2+(Y_c^i-y_{4a})^2}+I_{4b}\frac{y_{4b}-Y_c^i}{(X_c^i-x_{4b})^2+(Y_c^i-y_{4b})^2}+I_{4c}\cdot\frac{y_{4c}-Y_c^i}{(X_c^i-x_{4c})^2+(Y_c^i-y_{4c})^2}\right)\right| \quad (2)$$

$$b_y^i = \frac{\mu_0}{2\pi}\left|\left(I_{1a}\frac{X_c^i-x_{1a}}{(X_c^i-x_{1a})^2+(Y_c^i-y_{1a})^2}+I_{1b}\frac{X_c^i-x_{1b}}{(X_c^i-x_{1b})^2+(Y_c^i-y_{1b})^2}+I_{1c}\frac{X_c^i-x_{1c}}{(X_c^i-x_{1c})^2+(Y_c^i-y_{1c})^2}+\ldots+I_{4a}\frac{X_c^i-x_{4a}}{(X_c^i-x_{4a})^2+(Y_c^i-y_{4a})^2}+I_{4b}\frac{X_c^i-x_{4b}}{(X_c^i-x_{4b})^2+(Y_c^i-y_{4b})^2}+I_{4c}\frac{X_c^i-x_{4c}}{(X_c^i-x_{4c})^2+(Y_c^i-y_{4c})^2}\right)\right| \quad (3)$$

$$(b_x^j)^2+(b_y^j)^2 \leqslant B_{\max}^{gen2} \quad (4)$$

$$(b_x^l)^2+(b_y^l)^2 \leqslant B_{\max}^{\exp 2} \quad (5)$$

$$(x_{m,a}-x_{m,b})^2+(y_{m,a}-y_{m,b})^2=d^2 \quad (6)$$

$$(x_{m,a}-x_{m,c})^2+(y_{m,a}-y_{m,c})^2=d^2 \quad (7)$$

$$(x_{m,b}-x_{m,c})^2+(y_{m,b}-y_{m,c})^2=d^2 \quad (8)$$

$$\frac{x_{1,3a}+x_{1,3b}+x_{1,3c}}{3}=-x_{lateral} \quad (9)$$

$$\frac{x_{2,4a}+x_{2,4b}+x_{2,4c}}{3}=x_{lateral} \quad (10)$$

$$\frac{y_{1,2a}+y_{1,2b}+y_{1,2c}}{3}=y_{\sup gal}-t_1 \quad (11)$$

$$\frac{y_{3,4a}+y_{3,4b}+y_{3,4c}}{3}=t_2+y_{\sup gal}-h_{gal} \quad (12)$$

$$h_{gal}-(t_1+t_2)\geqslant d_{\min} \quad (13)$$

$$t_2+t_1+d_{\min}\leqslant h_{gal}-d_{ceiling}-d_{floor} \quad (14)$$

$$y_{\sup gal}\leqslant y_{\sup gal\ \min} \quad (15)$$

$$y_{\sup gal}-h_{gal}\geqslant y_{gal\max} \quad (16)$$

$$x_m\leqslant l_{\max}-d_{wall} \quad (17)$$

$$t_2\geqslant d_{floor} \quad (18)$$

$$t_1\geqslant d_{ceiling} \quad (19)$$

$$i=1,\ldots,(k_1+k_2)\ ,\ j=1,\ \ldots,\ k_1, l=1,\ \ldots,\ k_2,\ m=1,\ \ldots\ 4$$

Where the variables are: b_x^i and b_y^i , modules of phasors of horizontal and vertical projections of magnetic field phasors generated by all the *i* cables at the evaluation points of the measurement areas, (μT); $x_{lateral}$, horizontal coordinate to the centre of the right bundles of cables, (m); (y_{supgal}), vertical coordinate of the ceiling of the tunnel, (m); (x_{ml},y_{ml}), coordinates of the center of the *l*-cable in the *m*-bundle of cables, (m); t_1 distance from uppers bundles of cables to the tunnel ceiling, (m); and t_2 distance from lower bundles of cables to the floor, (m). The constants are: μ_0, permeability of free space, (H m^{-1}); I_{il} , phasor of currents flowing through the *i*-bundle of cables, phases *l = {a, b, c}*, (A); B_{maxgen}, maximum magnetic field allowed for general public in the external to tunnel evaluation plane, (μT); B_{maxexp}, maximum magnetic field allowed for occupational public in the area with human transit in tunnel is permitted, (μT); *d*, distance between two centers of cables in a bundle, (m); d_{min}, minimum distance allowed between two centers of cable bundles, (m); h_{gal} height of the tunnel, (m); d_{floor} and $d_{ceiling}$ the minimum distances allowed from the centres of cable bundles to floor and ceiling of the tunnel, (m); d_{wall}, fix distance from centers of cable bundles to walls of the tunnel, (m); l_{max}, maximum horizontal distance allowed from the vertical wall of the tunnel and the horizontal reference, (m); $y_{supgallmin}$, minimum depth allowed for the ceiling of the tunnel for security reasons, (m); y_{galmax}, maximum depth allowed for floor of the tunnel for construction and security, (m); k_1, number of evaluation points in the external measurement plane; k_2, number of evaluation points in the internal area.

The geometry of the tunnel is shown in Fig. 1. In a first approach, a symmetrical solution is searched. The cable bundles are allocated at the same horizontal distance from the center of the tunnel, at right and left. Also, the two upper cables and the two lower ones share the same vertical coordinates. The height of the tunnel h_{gal} is standard and fixed, 2.5 m. The tunnel can more or less buried and more or less wide in function of the magnetic restrictions and costs.

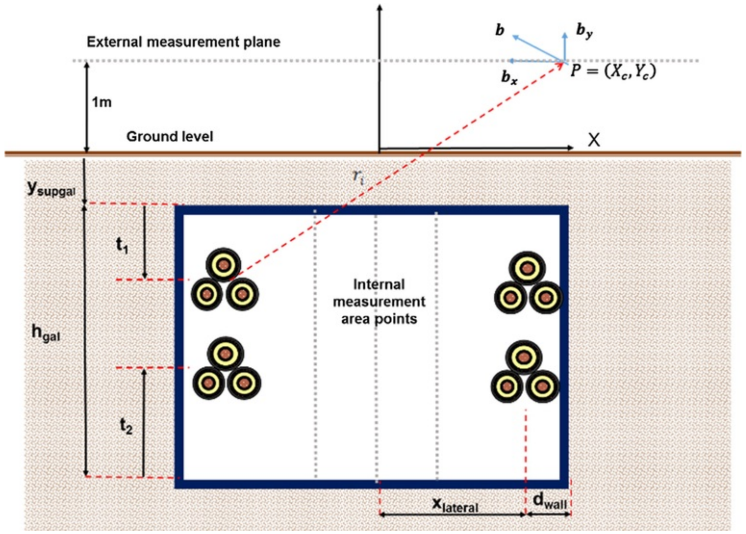


Fig. 1 Tunnel and magnetic field generated by a conductor at point *k*.

Main fees associated with the installation of underground transmission lines in tunnel are related with the cost of precast pieces of concrete that constitute the tunnel itself, civil construction and right-of-path costs. These costs can be associated to horizontal, vertical and volumetric terms. First term of (1) considers costs per unit related with variable horizontal costs of tunnel (C_{VarGal}) and occupation of land (c_x). The second and third terms of (1) consider vertical (c_y) and volumetric (c_{vol}) costs per unit, due to digging and shoring operations. The total cost of the tunnel is the sum of the three first terms plus the fixed cost, related with the fixed cost of manufacturing, the material of the two vertical walls that form the tunnel and the cost of the cables, i.e., a fixed cost C_{FixGal} does not included in the objective function.

To facilitate future maintenance actions, the cable bundles are preferably allocated far from floor and ceiling. The fourth term of the objective function maximizes these distances, with a small recompense coefficient c_p as 0.5 (€/m), much lower than the costs of first three terms of (1).

To limit the maximum magnetic fields, two measurement areas are considered, see Fig. 1. One, for limiting exposure of the general public, it is the horizontal line one meter above the terrain, with $k_1 = 51$ measurement points separated 0.2 m between them, representing a 10 m length line. The other one is the central area of the tunnel, with $k_2 = 78$ measurement points allocated in the intersections of three rows (the central axis and two others rows detached 0.6 m at left and right) and 26 lines (from floor to ceiling, with separations of 0.1 m between them). In (2) and (3), the modules of phasors of horizontal and vertical components of the magnetic field at each one of the measurement points are calculated. Some constructive solutions can be used for tunnels, but they are usually built of concrete reinforced with iron bars. For simplicity, the effect of reinforcement bars in the calculation of magnetic fields is not considered in the analysis, as variations in the structure of the terrain. However, they can be included in the formulation, when applicable. Magnetic shields are not represented in the optimization problem.

The square module of the magnetic field at external horizontal plane measurement points is restricted to the square of a specified maximum value B_{maxgen}, considering general public restrictions (4). In the internal area, the specified maximum value of restriction is B_{maxexp}, for occupational public (5).

Three cables constitute each bundle of cables, creating an equilateral triangle specified in (6)–(8). In the algorithm, the optimal rotated position of Fig. 2.a is calculated, increasing magnetic field compensation. In some cases, for constructions constraints, bundles' positions can be approximated to the more conventional bundle cable arrangement, Fig. 2.b.

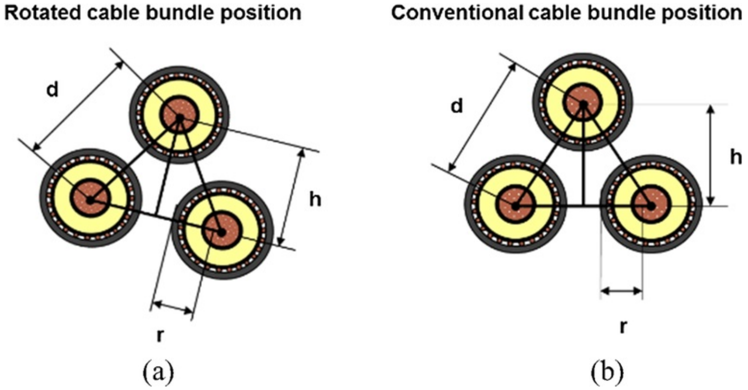


Fig. 2 Geometrical diagram of conventional and rotated bundle cables.

The position of the centers of cable bundles in function of lateral distances to the vertical axis of the tunnel ($x_{lateral}$) and the distances to the floor and ceiling of the tunnel (t_1 and t_2) are defined by Eqs. (9)–(12). Two centers of cable bundles are in the left wall of the tunnel (bundle 1 and 3) and the others two in the right wall (bundle 2 and 4). Pairs of cable bundles are constrained to have the same depth. This symmetry could facilitate further maintenances and the enlargement of the number of circuits in the tunnel.

For symmetry reasons, in (9)–(12) both walls have the same distance to the center of the tunnel. Symmetrical solutions can be optimal for balanced circuits. However, in real applications, each circuit transports different power and current. In the present case, historical data of the cables are used, showing different currents in each circuit all the time. Asymmetric galleries with different distances from walls of the tunnel to the maintenance path could give cost benefits. Asymmetric galleries can be calculated, replacing (9) and (10) for (20) and (21).

$$\frac{x_{1,3a}+x_{1,3b}+x_{1,3c}}{3} = -x_{lateral1} \quad (20)$$

$$\frac{x_{2,4a}+x_{2,4b}+x_{2,4c}}{3} = x_{lateral2} \quad (21)$$

where $x_{lateral1}$ is the distance of two right cable bundles to the center of the maintenance path and $x_{lateral2}$ is the distance of the left cable bundles to the same center.

Separation between the cables affects the interaction of the magnetic fields, [7,8]. In the present study, the results of simulations using distances between cables in bundles equal to $d = 0.3$ m and a minimum distance between bundles in the tunnel of $d_{Min} = 0.7$ m, specified in (13) and (14), are presented.

For security and construction reasons, the minimum depth allowed for the ceiling of the tunnel $y_{supgalmin}$ is 0.5 m and the maximum depth for the floor of the tunnel y_{maxgal} is 5 m, (15) and (16). Because of the nature of urban terrain, maximum distance between walls of tunnel is limited to 8 m, (17), where l_{max} is 4 m. For maintenance reasons, cable bundles are allocated at a minimum distance of the floor ($d_{floor} = 0.2$ m) and the ceiling ($d_{ceiling} = 0.2$ m) of the tunnel, (18) and (19).

2.2 Calculation of mean coordinates for four cables bundles in M scenarios

Currents in circuits in electrical power systems vary along time, depending on changes in demand and generation. The optimal design of the system configuration should then take into account the statistical distribution of the operating values. To this aim, the calculation of the optimal design is based on actual data gathered from a real case, considering three years of hourly current recordings of four underground circuits with the same path in the proximity of a substation. The proposed statistical approach is based on simulation of random scenarios by bootstrap resampling from the recorded data. Here, a scenario means a vector of observations of currents, corresponding to a unit time. A set of M random samples, with replacement, compound the scenarios to be analyzed. This resampling approach allows each bootstrap sample to be drawn from the same multivariate empirical distribution, which is exactly what we want to do when we take a sample from the population. In addition, the replacement allows each bootstrap sample to be independent of the others, which is also a desirable property in random sampling. For each one of the M samples, the solution of optimization problem (1)–(19) results in M optimal positions of cables. The final optimal configuration will be located at some central position of the M optimal configurations of the cables. Given the nonlinearity of the problem, this final mean coordinates are obtained in a second optimization problem that consider not only the statistical variability of the actual data, represented by the bootstrapped samples, but also geometrical restrictions. This optimal configuration is solved as follows:

$$\min\ h(x)=\sum_{m=1}^{M}\sum_{i=1}^{n}((s_{ia}^{m})^2+(s_{ib}^{m})^2+(s_{ic}^{m})^2+(t_{ia}^{m})^2+(t_{ib}^{m})^2+(t_{ic}^{m})^2) \tag{22}$$

s.t.Eqs. (6)–(17).

$$x_{il}-s_{il}^{m}=x_{il}^{m} \tag{23}$$

$$y_{il}-t_{il}^{m}=y_{il}^{m} \tag{24}$$

$i=1,\ldots,n$, $l=a,b,c$, $n=4$, $m=1,\ldots,M$ .Where the variables are: (x_{il},y_{il}), mean coordinates of the l-cable in the i-bundle of cables of the optimal mean arrangement; and s_{il}^{m},t_{il}^{m} , horizontal and vertical difference from (x_{il},y_{il}) to each one of the (x_{il}^{m},y_{il}^{m}) coordinates of centers of the l-cable in the i-bundle of cables, for the m sample of currents. In the present optimization problem, (x_{il}^{m},y_{il}^{m}) are fixed values, previously calculated using the optimization problem (1)–(17) for each one of the M scenarios.

The objective function (22) is the addition of the square differences between coordinates of the centers of cable l in the bundle of cables i of sample m to the coordinates of the centers of the cables of the optimal mean arrangement s_{il}^{m},t_{il}^{m} . In total, for 4 cable bundles, (24 times M) terms constitute the objective function. In the present formulation, all the differences are equally penalized. However, solutions prioritizing less costly positions can also be found. Eqs. (6)–(17) express geometrical restrictions that cables and bundles must respect. Also, the dimensions of the tunnel for the mean solution are calculated in these equations. Eqs. (23) and (24) calculate the differences between the mean centers of the cables and each one of the samples.

2.3 Multi-scenarios optimization

In the Multi-Scenarios approach, N_{sc} selected scenarios are chosen such that they correspond to a cluster of representative situations. The optimal dimension of tunnel and positions of cables are then calculated, minimizing the costs for all the scenarios simultaneously. The purpose of this approach is to constraint the magnetic field for a cluster of representative events, like those corresponding to extreme currents or some particular combination of currents that can have a high impact in terms of magnetic fields. The proposed optimization problem is formulated as follow.

$$\min\ f(x,y,t_1,t_2)=2(c_{VarGal}+c_x)(x_{lateral}+d_{wall})+c_y(h_{gal}-y_{\sup gal})+2c_{vol}(x_{lateral}+d_{wall})(h_{gal}-y_{\sup gal})-c_p(t_1+t_2) \tag{25}$$

s.t.

$$b_{xq}^{i}=\frac{\mu_0}{2\pi}\left|\left(\mathrm{I}_{1qa}\frac{y_{1a}-Y_c^i}{(X_c^i-x_{1a})^2+(Y_c^i-y_{1a})^2}+\mathrm{I}_{1qb}\frac{y_{1b}-Y_c^i}{(X_c^i-x_{1b})^2+(Y_c^i-y_{1b})^2}+\mathrm{I}_{1qc}\cdot\frac{y_{1c}-Y_c^i}{(X_c^i-x_{1c})^2+(Y_c^i-y_{1c})^2}+\ldots+I_{4qa}\frac{y_{4a}-Y_c^i}{(X_c^i-x_{4a})^2+(Y_c^i-y_{4a})^2}+I_{4qb}\frac{y_{4b}-Y_c^i}{(X_c^i-x_{4b})^2+(Y_c^i-y_{4b})^2}+I_{4qc}\cdot\frac{y_{4c}-Y_c^i}{(X_c^i-x_{4c})^2+(Y_c^i-y_{4c})^2}\right)\right| \tag{26}$$

$$b_{yq}^{i}=\frac{\mu_0}{2\pi}\left|\left(\mathrm{I}_{1qa}\frac{X_c^i-x_{1a}}{(X_c^i-x_{1a})^2+(Y_c^i-y_{1a})^2}+\mathrm{I}_{1qb}\frac{X_c^i-x_{1b}}{(X_c^i-x_{1b})^2+(Y_c^i-y_{1b})^2}+\mathrm{I}_{1qc}\frac{X_c^i-x_{1c}}{(X_c^i-x_{1c})^2+(Y_c^i-y_{1c})^2}+\ldots+I_{4qa}\frac{X_c^i-x_{4a}}{(X_c^i-x_{4a})^2+(Y_c^i-y_{4a})^2}+I_{4qb}\frac{X_c^i-x_{4b}}{(X_c^i-x_{4b})^2+(Y_c^i-y_{4b})^2}+I_{4qc}\frac{X_c^i-x_{4c}}{(X_c^i-x_{4c})^2+(Y_c^i-y_{4c})^2}\right)\right| \tag{27}$$

$$(b_{xq}^{j})^2+(b_{yq}^{j})^2\leqslant B_{\max}^{gen2} \tag{28}$$

$$(b_{xq}^{l})^2+(b_{yq}^{l})^2\leqslant B_{\max}^{\exp 2} \tag{29}$$

Eqs. (6)–(19).

$i=1,\ldots,(k_1+k_2)$

, $j=1,\ldots,k_1$, $l=1,\ldots,k_2$, $q=1,\ldots,N_{sc}$

Objective function (25) is the same than in the optimization problem of Section 2.1. However, one unique position of cables and tunnel is calculated, regarding the N_{sc} chosen scenarios. In (26) and (27), for the N_{sc} scenarios of representative currents, the horizontal and vertical components of the magnetic field at each one of the measurement points are calculated. Eqs. (28) and (29) limit the maximum magnetic field allowed for the general and occupational public in each scenario. Geometrical restrictions to the position of cables, bundles and dimensions of tunnel in (6)–(19) are applicable to this optimization problem. As in Section 2.1, if the asymmetric configuration is calculated, (8) and (9) is substituted by (20) and (21).

In the present work, 6 representative events are considered. Instead of using a single scenario for each event, we form a cluster with the 3 nearest scenarios, with the aim of reducing sampling variability and increase robustness. Therefore, a total of Nsc = 18 representative scenarios are selected and represented in the optimization problem, as follows:

- From the historical data, the three scenarios with the maximum and the three ones with the minimum differences of modules between the two circuits with largest modules of currents.
- From the historical data, the three scenarios with the maximum and the three scenarios with the minimum differences of phase angle.
- From the M scenarios solved in Section 2.2, the three scenarios with maximum costs and the three scenarios with minimum costs.

3 Case of study

In this work, a real case of four balanced underground power circuits of single core XLPE cables, with a cupper conductor of 2,500 mm^2, maximum thermal current 1700 A and 220 kV, is studied. The four circuits are connected to the same substation and share path in its proximity. Instantaneous values of active and reactive power have been recorded every hour for three years. There is a total of 26.280 valid recordings. A small amount of data was lacking in one cable for a month, due to a measure equipment fault. These missing values were removed from the historical data, only using valid recordings in the study. Proportional active and reactive currents, I_d e I_q, have been calculated and are shown in Figs. 3 and 4.

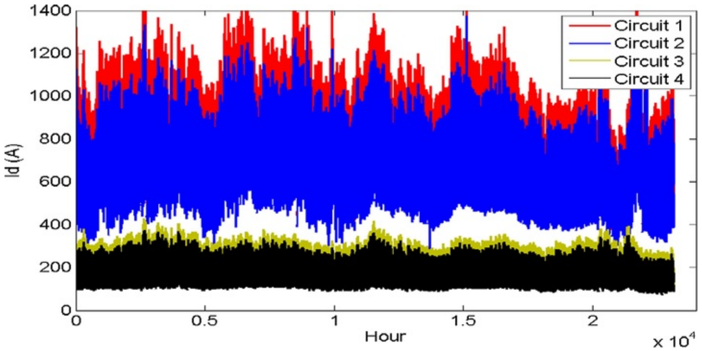


Fig. 3 Active Currents in the four circuits – I_d (A).

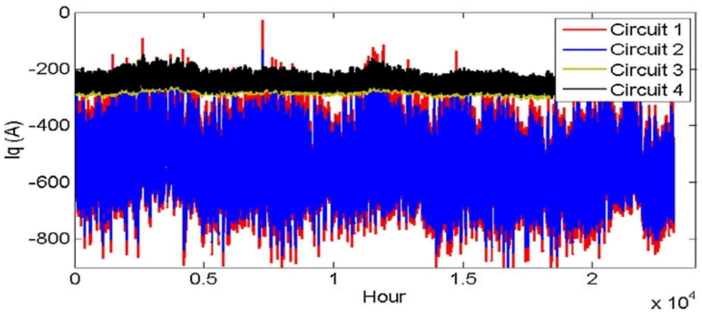


Fig. 4 Reactive currents in the four circuits – I_q (A).

Figs. 3 and 4 reveals that the statistical properties of the series of currents are stable along time. There is an absence of patterns of growth or decay, and the daily and weekly seasonal (stochastic) patterns are stable over time. Besides, the time series are large enough to reflect the actual variability. Consequently, resampling from the unconditional distributions can provide a representative sample of the multivariate distribution of the currents. In the present case, real historical data is available and used in the study. For new installations, historical data is not existing. Therefore, statistical data from similar cables or forecasted data obtained by simulations could be used to calculate the optimal dimensions of cables and tunnel.

To perform the statistical approach, $M = 150$ random samples of currents in Figs. 4 and 5 are sorted. For each one of these samples, optimization problem (1)–(19) is solved. In these simulations, the costs per unit are obtained from a general reference for construction costs: $c_{FixGal} = 210$ €/m, $c_{VarGal} = 70$ €/m, $c_x = 10$ €/m^2, $c_y = 14.6$ €/m^2 and $c_{vol} = 6.5$ €/m^3 [26]. In (1), only variable construction costs are considered; the costs of the cables themselves are not included. In fifth term of (1), $c_p = 0.5$.

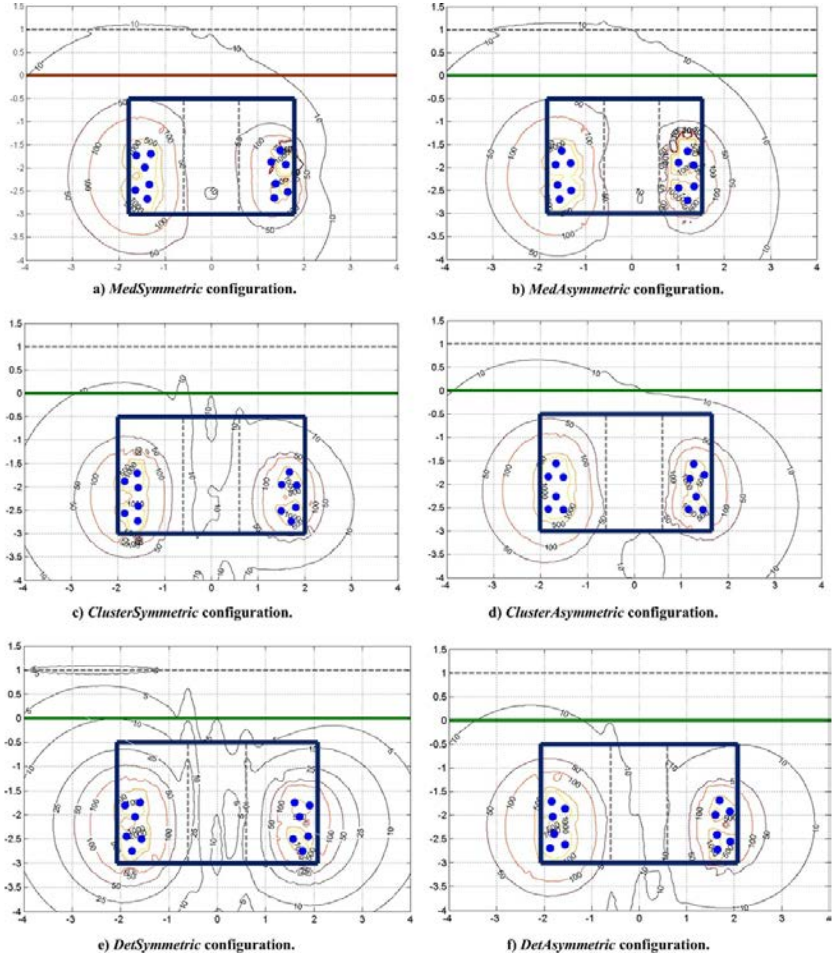


Fig. 5 Isolines of the Magnetic Field, Case A.

Regarding geometrical constraints (13)–(17), following values are used: $d_{min} = 0.7$ m, $y_{supgalmin} = -0.5$ m, $y_{galmax} = -5$ m, $l_{max} = 8$ m, $d_{ceiling} = d_{floor} = 0.45$ m, $h_{gal} = 2.5$ m and $d_{wall} = 0.35$ m. MatLab is used to solve the optimization problems.

4 Results

The traditional solution, a unique deterministic calculation of the position of bundles without rotation and symmetrical, is compared with five alternative optimal configurations. They are labelled as follows:

- *DetSymmetric*: deterministic calculation of the optimal configuration, solving once the optimization problem (1)–(17). As presented in Fig. 4, two circuit have similar high values of currents (circuits 1 and 2) and in the other two (3) and (4) flow less currents. To simulate this pattern, in two circuits the maximum thermal current (1700 A) is considered and in the other two (3) and (4) the maximum current recorded (360 A). This calculation is similar to the solutions studied in most of the literature [8–15].
- *DetAsymmetric:* Like in previous case, but allowing asymmetric tunnels. Thus, constraints (20) and (21) are used, instead of (9) and (10).
- *MedSymmetric:* From historical data, $M = 150$ scenarios of instantaneous currents are randomly sorted. In each scenario, optimization problem (1)–(19) is solved. Then, the mean arrangement of cables is calculated following the procedure of

Section 2.2.

- *MedAsymmetric:* Like previous method, but considering asymmetric tunnels. Constraints (20) and (21), instead of (9) and (10), are used.
- *ClusterSymmetric:* Solving optimization problem of Section 2.3 based on the previously defined 18 representative currents.
- *ClusterAsymmetric:* As *ClusterSymmetric*, permitting asymmetric tunnels.

The calculation of optimal configurations for tunnels and cables with heavy magnetic constraints and time varying currents is a very difficult task. Two cases are here considered:

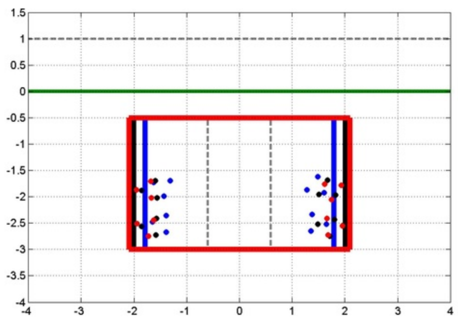
- *Case A:* $B_{maxgen} = 10\,\mu T$ *and* $B_{maxexp} = 50\,\mu T$
- *Case B:* $B_{maxgen} = 3\,\mu T$ *and* $B_{maxexp} = 15\,\mu T$

4.1 Case A: $B_{MAXGEN} = 10\,\mu T$ and $B_{MAXEXP} = 50\,\mu T$

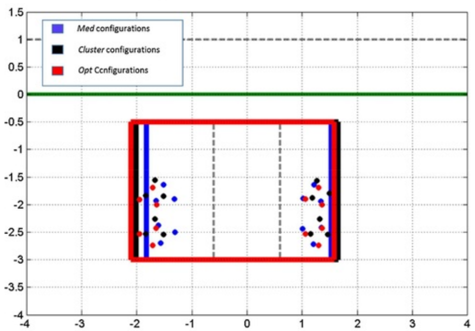
MedSymmetric, *MedAsymetric, ClusterSymmetric, ClusterAsymmetric, DetSymmetric* and *DetAsymmetric* configurations are calculated using Case A magnetic field limits. After that, all the hourly recorded values of Figs. 3 and 4 are applied to the configurations. The resulting scheme of the tunnel, position of cables and some isolines of magnetic field are depicted in Fig. 5.

Due to the compensation of magnetic fields, best cost results are obtained for dispositions with similar modules of currents (circuits 1 and 2 and circuits 3 and 4) allocated in the same wall of the tunnel. As expected, in asymmetric configurations, the larger currents are allocated farther from the maintenance path. As observed in isolines of Fig. 5, *Det* and *Cluster* configurations can maintain the specified magnetic limits for all historical data. However, *Med* configurations have some external and internal points overpassing the magnetic limits, when applied the historical data at these configurations.

In Fig. 6, a comparison between symmetrical and asymmetrical solutions are shown. *Med* configurations (in blue) result in lowest width, followed by *Cluster* (in black) and *Det* configurations (in red). It is remarkable that asymmetric configurations need smaller tunnels than symmetric ones.



a) *Symmetric* configurations.



b) *Asymmetric* configurations.

Fig. 6 Comparison of dimensions of tunnels, Case A.

Table 1 shows the cost and the maximum value of the 95th percentiles values of magnetic field, when applied the currents of Figs. 3 and 4 to the six configurations. *Med* configurations are cheaper, followed by *Cluster* and *Det* configurations. *DetSymmetric and DetAsymmetric* configurations are 9.3 and 5.1 €/m more expensive than *MedSymmetric* and *MedAsymmetric* positions, respectively. In general, asymmetric solutions result in cheaper tunnels, reducing the distances of the circuits 3 and 4, with lower currents, to the maintenance path.

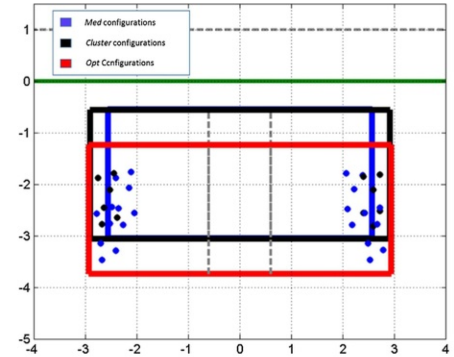
Table 1 Cost and values of the 95th percentile of magnetic field, Case A.

	Symmetric Configurations			Asymmetric Configurations		
	95th Percentile of Magnetic Field (µT)		Cost (€/m)	95th Percentile of Magnetic Field (µT)		Cost (€/m)
	Exterior	Interior		Exterior	Interior	
Med	11.6	31.5	654	12.7	37.6	630
Cluster	8.8	18.7	696	8.8	19.4	661
Det	6.1	17.2	715	6.5	21.1	663

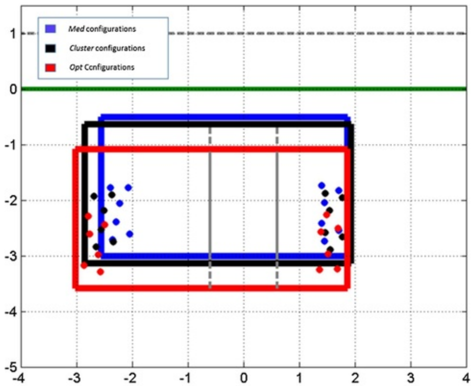
4.2 Case B: $B_{maxGEN} = 3$ µt and $B_{maxEXP} = 15$ µt

As previously stated, some states (as Italy and Switzerland) require stronger limitations of magnetic fields for general public. Therefore, in Case B external constraints are restricted to 3 µT and internal constraints have a maximum value of 15 µT. New configurations are calculated and the historical data of the 3 years is applied to these configurations. Tunnels are bigger and more expensive than in the previous case. As before, circuits with higher modules of currents (Circuits 1 and 2) are placed in the same wall of the tunnel and asymmetric tunnels provide smaller and cheaper solutions.

In Fig. 7, the geometry of tunnels is depicted for the six configurations. It must be highlighted that *Det* configuration requires tunnels about half a meter deeper than *Med* and *Cluster* configurations. Asymmetrical dispositions are narrower than symmetrical ones.



a) *Symmetric* configurations.



b) *Asymmetric* configurations.

Fig. 7 Comparison of dimensions of tunnels, Case B.

Table 2 shows the cost and the maximum value of the 95th percentiles of the values of magnetic field. *MedAsymmetric* is the cheapest configuration. *DetAsymmetric* and *ClusterAsymmetric* configurations are 24.7% and 6% more expensive than *MedAsymmetric*. However, *Med* configurations fail to maintain the external magnetic field constraint, reaching 3.8 or 3.8 µT for a limit of 3 µT. In this sense, *Cluster* configurations are 5.8% (symmetrical) and 4.7% (asymmetrical) cheaper than conventional *DetSymmetric* and *DetAsymmetric* configurations, producing lower magnetic fields while respecting the specified magnetic field limits for all historical data.

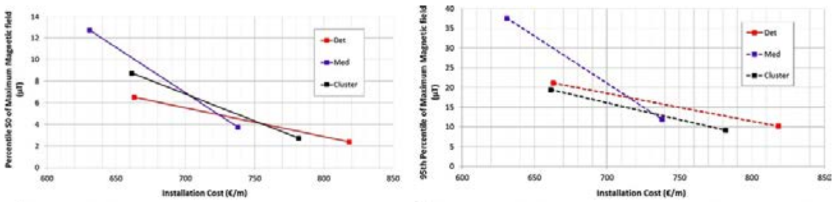
Table 2 Cost and values of the 95th percentile of magnetic field, Case B.

	Symmetric Configurations			Asymmetric Configurations		
	95th Percentile of Magnetic Field (µT)		Cost (€/m)	95th Percentile of Magnetic Field (µT)		Cost (€/m)
	Exterior	Interior		Exterior	Interior	
Med	3.8	9.7	809	3.8	12.0	738
Cluster	2.8	9.2	880	2.7	9.2	782
Det	3.0	8.5	931	2.4	10.2	818

4.3 Cost comparisons

In Fig. 8, the curves of maximum magnetic fields and costs for *DetAsymmetric*, *MedAsymmetric* and *ClusterAsymmetric* configurations are displayed. As observed, *DetAsymmetric* is more expensive than the other two configurations.

Moreover, for low values of magnetic field in this configuration, a relatively small reduction of the magnetic fields results in a significant increase of costs. *MedAsymmetric* configuration performs better, in this example, in the external plane with *ClusterAsymmetric* working better for the internal measures.



a) Magnetic field in the external plane, asymmetrical configurations. **b) Magnetic field in the maintenance path, asymmetrical configurations.**

Fig. 8 95th Percentile of magnetic field in measurement plane vs. costs.

5 Conclusions

This work proposes and compares methods for optimizing allocation of 4 cable bundles and tunnel dimensions for underground lines allocated in tunnels, with stochastically time-varying currents flowing through them and considering maximum magnetic fields, geometrical constraints and installation cost. A real-world case with four cable bundles and three years of historical data is studied. Two statistical configurations, namely, the mean calculation and a cluster of representative scenarios, are compared with the usual deterministic calculation method. Also, symmetrical and asymmetrical disposition of cables are considered in the study.

From the results, the proposed statistical approach is found far more convenient than the traditional deterministic method, providing significant reduction of construction cost, complying with the magnetic field restrictions. Mean arrangement of cables provides cheaper solutions, passing beyond specified magnetic limits in some scenarios of the historical data. The clustering approach results in interesting reductions of costs, strictly reaching magnetic field constraints.

Uncited reference

[6]

Acknowledgement

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Highlights

- In the present paper, new algorithms are proposed and analyzed to obtain optimal disposition of cables and dimensions of tunnels, minimizing construction costs and magnetic field for both general and occupational public.
- Time changing currents are considered, resulting in a so-called statistical approach. Real data from a system of four three-phase single-core cables are used in the study.
- The proposed statistical approach provides cheaper solutions and with lower generated magnetic field than conventional methods.
- Symmetrical and asymmetrical disposition of cables are also considered in the study.

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* Proposed statistical approach provides cheaper solutions and lower magnetic fields.
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