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

Víctor J. Hernández Jiménez[a,b], Edgardo D. Castronuovo[b,*], Ismael Sánchez[b,c]

[a] Red Eléctrica de España, P°Conde de los Gaitanes, 177, 28109 Alcobendas, Madrid, Spain
[b] Universidad Carlos III de Madrid, Avda. de la Universidad, 30, 28911 Leganés, Madrid, Spain
[c] Universidad de Piura, Avda. Ramón Múgica, 131, Urb. San Eduardo, Piura, Peru

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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.

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

* Corresponding author.
E-mail addresses: vjhdez@ree.es (V.J. Hernández Jiménez), ecastron@ing.uc3m.es (E.D. Castronuovo), ismael.sanchez@uc3m.es (I. Sánchez).

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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).

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

s.t.

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

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

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

$$(b_x^l)^2+(b_y^l)^2\leqslant B_{\max}^{exp2} \tag{5}$$

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

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

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

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

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

$$\frac{y_{1,2a}+y_{1,2b}+y_{1,2c}}{3}=y_{supgal}-t_1 \tag{11}$$

$$\frac{y_{3,4a}+y_{3,4b}+y_{3,4c}}{3}=t_2+y_{supgal}-h_{gal} \tag{12}$$

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

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

$$y_{supgal}\leqslant y_{supgal\ \min} \tag{15}$$

$$y_{supgal}-h_{gal}\geqslant y_{gal\max} \tag{16}$$

$$x_m\leqslant l_{\max}-d_{wall} \tag{17}$$

$$t_2\geqslant d_{floor} \tag{18}$$

$$t_1\geqslant d_{ceiling} \tag{19}$$

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