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ORIGINAL RESEARCH

Increasing the ampacity of underground cable lines by optimising the thermal environment and design parameters for cable crossings

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Abstract
The problem of optimising the thermal environment and design parameters of underground cable lines for cable crossings with the aim of increasing the ampacities of cables is considered in this paper. Particle swarm optimisation (PSO) algorithm, formulated as a continuous non-linear optimisation problem with constraints, for solving this hot spot problem is applied. It is found, using the PSO algorithm, that there are a suitable size of cable bedding and an arrangement of cables within that bedding, which can eliminate or significantly mitigate the hot spot effect without the use of any additional cooling equipment. In this manner, the ampacities of both crossing cable lines increase by about 15% on average with respect to the case of a similar crossing with installation parameters commonly used. In addition, it is shown how the cross-sectional areas of the conductors and metal screens and the metal screen bonding methods affect the optimal solution.

1 | INTRODUCTION

In addition to the operating voltage, the transmission performance of an underground cable line is determined by its current carrying capacity (ampacity) that is limited by the most unfavourable thermal conditions (thermal environment) along the entire cable line route. Such hot spots occur when underground cable lines cross various heat sources, mainly other power cables and heating pipelines [1, 2]. This is often the case in urban areas. Accordingly, the hot spots represent the areas where the conductor temperature may be much higher than the ones along the remaining parts of the cable line. In order to protect the cable insulation from overheating in a hot spot, it is necessary to reduce the ampacity in line with the thermal environment in that hot spot, using the corresponding derating factor (DF) [3]. The DF represents the ratio of the ampacity when taking into account the hot spot effect to the ampacity corresponding to the cable line design without any hot spot [4].

Many utilities ignore the derating of ampacities of cables that are crossed by other heat sources (in particular for low and medium voltages), while some other utilities apply a reduction of up to 5% [3]. In [3], it was shown that a 20% reduction is often required for typical installation conditions and common cable constructions. By ignoring the DFs or by taking into account their small values, cable failures in hot spots will become inevitable once the conductor temperature values rise above the corresponding continuously permissible temperature [5, 6].

By restructuring the electricity industry and introducing the electricity market around the world, the transmission lines are becoming more and more loaded and, in most instances, operating with the maximum possible currents, that is. ampacities [7]. For any cable line for transmission, the ampacity corresponds with one of its hot spots, if they exist. Accordingly, eliminating the hot spots will result in a considerable increase in the transmission performance of that line.

There are not too many publications in the literature that deal with cable crossings. In [2, 5], the authors proposed the use of special cable beddings and cooling systems with heat collecting pipes to eliminate the effect of hot spots. A similar cooling system with heat collecting pipes can also be found in [8]. Nowadays, the application of thermally stable bedding material along the entire route of any cable line represents an obligatory requirement, and not only in its hot spots, so that the hot spots still, with respect to the rest of the route, limit the transmission performance of such a cable line. On the other hand, the use of a cooling system with heat collecting pipes to eliminate the hot spots takes up lots of extra space both below (heat collecting pipes) and above (radiator) of the ground surface. In urban areas, this additional space is often not readily available.

Mitigation of a cable hot spot using a gravitational water cooling system is considered in [9]. This cooling system requires space for a water reservoir near the hot spot, which, as mentioned previously, is often not available. Its cooling efficiency directly depends on the difference between the laying depths of the lower pipe (which is installed below power cables) and the upper pipe (which is installed above power cables), and thus on the difference between the densities or weights of the water in them. When the laying depth of power cables is small, the required difference in laying depths between the upper and lower pipes cannot be achieved, especially if it is known that the highest point of the upper pipe must be below the water reservoir, which is buried and has a certain height.

The applications of water cooling systems to improve the transmission performance of heavily loaded cable lines around the world are reviewed in [9]. All cooling systems require the installation of equipment such as pipes, reservoirs, and pumps (if the forced circulation of the water coolant is applied). The equipment requires additional space, implies additional costs, can break down (if pumps are used), or can be damaged due to construction works.

Furthermore, it turned out that it is not possible to solve such a problem using the finite element method (FEM) and FEM-based software tools (COMSOL, ANSYS, etc.) due to a number of common restrictions. Since the effect of a typical source of heat practically disappears for about 6 m from the cable crossing [3, 10], a three-dimensional model of similar dimensions would be necessary for the corresponding thermal FEM-based analysis of the cable crossing. The sizes of finite elements discretising the associated computational domain must be very small due to the small thicknesses of individual cable construction layers (especially metal screens). Accordingly, the number of finite elements would be so large that even today's powerful computers would not provide solutions (temperature distributions) within a reasonable time frame. On the other hand, if finite elements of larger dimensions are used, then there may be a wrong generation of finite elements within and around narrow blocks/layers (finite elements may overlap in these regions, which is not allowed), which occurs frequently, especially in three core cables.

There also are several commercial software tools that allow to calculate the ampacities for multiple cable crossings (Cableizer, CST Studio Suite, and Cable High Voltage). All of them calculate the DF in line with IEC 60287-3-3 standard, according to which all the soils surrounding one cable (or cables) are assumed to have uniform thermal conductivities. In addition, the application of FEM or any commercial software to find the optimal solution would require an analysis of a large number of combinations of design parameters affecting the solution. Thus, it would be a very time-consuming procedure as a large number of simulations are required.

A novel approach to increase the DF of two cable lines in their crossing is proposed in this paper. The approach takes into account the fact that the temperature of any conductor in both lines cannot exceed the corresponding continuously permissible temperature. The proposed approach is applicable in the design stage of each new cable line. For parts of an underground line route, where cables cross other heat sources, the procedure for optimising the thermal environment and design parameters can be applied to eliminate (or significantly mitigate) the hot spot effect without the use of additional cooling equipment. It is shown how the cross-sectional areas of the conductors and metal screens together with the metal screen bonding methods affect the optimal solution. The optimisation problem is solved analytically using the PSO algorithm.

By executing the PSO algorithm only once, the proposed approach enables design engineers and planners to select the optimal values of design parameters that provide the maximised ampacities for two cable lines crossing each other. The entire native soil surrounding the cable crossing is assumed to be completely dried out. The proposed approach deals only with the simplest and most typical cable crossing, however, it can also be applied to the case of multiple cable crossings. A flat arrangement of power cables is considered here in order to illustrate the concept, but the approach can also include other possible arrangements of cables in the two lines.

2 | PROBLEM FORMULATION

Figure 1 illustrates the crossing of two cable lines, each consisting of single-core cables in flat formation. It is assumed that the upper three cables (i.e. existing heat sources) already exist, and that, therefore, their laying depth and side-by-side spacing cannot be changed. It is also assumed that the installation of the lower three cables (i.e. planned underground line) is currently still in the planning phase.

An increase in temperature of the cables in the planned underground line, due to the close proximity of existing heat sources, depends on several parameters. The parameters that can be changed are as follows: width (W_2), height (H) and thermal resistivity (ρ_b) of the bedding material surrounding the cables in the crossing area, depth of the cable bedding centre (B), laying depth of the planned underground line (L_2), and axial spacing between cables in the planned underground line (S_2). Apart from ρ_b, the mentioned parameters represent design variables. All the design variables relevant to the problem under consideration are given in Figure 1.

The aim of the optimisation procedure conducted in this paper is to determine the optimal values for design variables

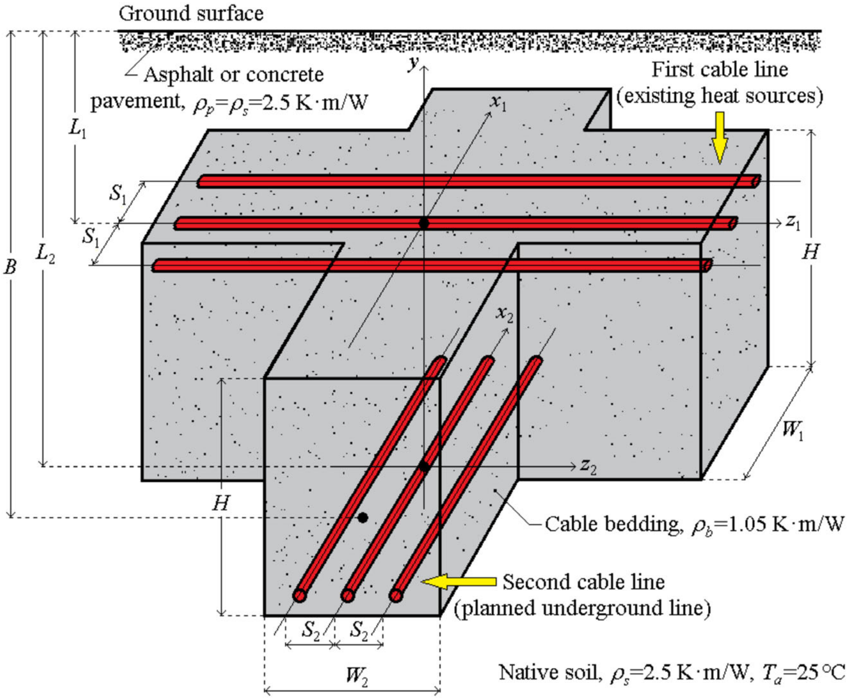

FIGURE 1 Typical crossing of two underground lines with single-core cables installed in flat formations

that provide maximum values of DFs for both cable lines, and thus maximise their ampacities with respect to the considered cable crossing. It is expected that, in the procedure for maximising the cable ampacities, the external thermal resistance of the planned underground line will tend to reduce the corresponding laying depth L_2, while the mutual thermal resistance between the planned underground line and the existing heat sources will tend to increase L_2. Accordingly, the planned underground line should be located as far as possible away from the existing heat sources. Similarly, there will be a non-monotonically increasing trend in the ampacity when the axial spacing between cables in the planned underground line S_2 increases and vice versa. In addition, mutual heating effects between cables in the planned underground line will increase with decreasing S_2, while the circulating currents in the metal screens of these cables will decrease with decreasing S_2. There are some other trends of variation for design variables affecting objective functions in a manner contrary to expectations. These trends depend on the cable construction, voltage level, cross-sectional areas of the conductors, and grounding of the metal screens. The optimal values for design variables, that maximise the ampacities of both underground lines with respect to the cable crossing area, can be obtained by balancing a combination of these mutual heating effects.

Finally, the cable conductors could carry higher ampacities if it can be ensured that the cable bedding is larger in size. In addition, there are physical and economic constraints that determine the width and height of the cable bedding. The cable bedding width is determined by the available soil zone intended for the installation of power cables (specifically, in urban areas). It is also economical to increase the cable bedding height until reaching approximately the final value of the curve that functionally connects the cable ampacity with the cost for cable bedding.

2.1 | Definition of an objective function and variables

Based on an analysis performed by the authors on the effects of design variables on some objective functions, the considered problem of hot spot mitigation is formulated as a continuous non-linear optimisation problem with constraints. The optimisation problem is solved by using the PSO algorithm.

The standard form of a continuous non-linear optimisation problem can be described mathematically as follows:

$$\text{minimise } F(\boldsymbol{x}) \tag{1}$$

$$\text{subject to } \boldsymbol{g}_i(\boldsymbol{x}) \leq 0, \quad i = 1, \ldots, m \tag{2}$$

$$\boldsymbol{h}_j(\boldsymbol{x}) = 0, \quad j = 1, \ldots, p \tag{3}$$

where $F(\boldsymbol{x})$ is the objective function to be minimised over the n-variable vector $\boldsymbol{x}$, $\boldsymbol{x}$ is the vector of design variables, $\boldsymbol{g}(\boldsymbol{x})$ is the vector consisting of m inequality constraints, and $\boldsymbol{h}(\boldsymbol{x})$ is the vector consisting of p equality constraints. In general, the vector (3) consists of p elements that can denote specific relationships between the design variables to be satisfied. In the case under consideration, there is no such relationship, so $p = 0$.

The vector of design variables, whose elements will be the subject of optimisation using the PSO algorithm, is defined as follows:

$$\boldsymbol{x} = [W_2\ H\ B\ L_2\ S_2]^{\mathrm{T}} \tag{4}$$

All elements of the vector $\boldsymbol{x}$ are defined previously and expressed in meters. The PSO is described in detail in [11].

The ampacity of the second cable line that takes into account the presence of the first cable line (existing heat sources) at the crossing area can be obtained by multiplying the steady-state ampacity related to the design of the second cable line outside the cable crossing by a derating factor

$$\mathrm{DF} = \sqrt{1 - \frac{\Delta\theta\,(0)}{\Delta\theta_{\max} - \Delta\theta_d}} \tag{5}$$

that takes into account the hot spot effect [4, 12]. In this equation, $\Delta\theta(0)$ is the temperature rise of the cable conductor due to crossing heat sources at the crossing area in K, $\Delta\theta_{\max}$ is the permissible temperature rise of the cable conductor above the ambient/soil temperature (T_a) in K, and $\Delta\theta_d$ is the temperature rise of the cable conductor due to dielectric losses in K.

If the DF for the case when the first cable line crosses the second one is DF_1, and if the DF for the case when the second cable line crosses the first one is DF_2 (according to Figure 1), then the sum $I_1{\cdot}DF_1 + I_2{\cdot}DF_2$ represents the first term of the objective function $F(\boldsymbol{x})$. The second term of this function represents the product of width and height of the cable bedding of the second cable line multiplied by 5 (in order to give equal importance to both terms of the objective function). Accordingly, the multi-objective function $F(\boldsymbol{x})$ that will be minimised has the following form:

$$F\,(\boldsymbol{x}) = -\,(I_1 \cdot DF_1 + I_2 \cdot DF_2) + 5 \cdot W_2 \cdot H. \tag{6}$$

The first term of the multi-objective function (Equation (6)) is negative because any standard optimisation problem involves minimising a function of several variables, subject to a set of constraints defined. The ampacities I_1 and I_2 appearing in Equation (6) are the steady-state ampacities of the first and second cable lines related to their designs outside the cable crossing, respectively. The ampacities are calculated using the equation of the IEC 60287-1-1 standard for underground power cables where partial drying-out of the surroundings can be expected (see Equation (7):

$$I = \left[\frac{\Delta\theta_{\max} - W_d\,[0.5T_1 + n\,(T_2 + T_3 + \nu T_4)] + (\nu - 1)\,\Delta\theta_x}{R_{ac}\,[T_1 + n\,(1+\lambda_1)\,T_2 + n\,(1+\lambda_1+\lambda_2)\,(T_3 + \nu T_4)]}\right]^{0.5} \tag{7}$$

The variables and parameters appearing in Equation (7) have the following meanings [13]: W_d is the dielectric losses per unit length in each phase in W/m, n is the number of conductors in each cable, $\nu = \rho_{s\mathrm{dry}}/\rho_s$ is the ratio of the thermal resistivities of the dry and moist ambient/soil zones, $\rho_{s\mathrm{dry}}$ and ρ_s are the thermal resistivities of the dry and moist soil zones, respectively, T_1 is the thermal resistance per phase between the cable conductor and metal screen in K·m/W, $T_2 = 0$ Km/W is the thermal resistance between the metal screen and armour layer, T_3 is the thermal resistance of the outer sheath in Km/W, T_4 is the thermal resistance of the surroundings in Km/W, $\Delta\theta_x$ is the temperature rise of the boundary between the dry and moist ambient/soil zones above the ambient/soil temperature in K, R_{ac} is the ac resistance of the cable conductor at its continuously permissible temperature in Ω/m, λ_1 is the ratio between the total losses in a metal screen and the total losses in the corresponding conductor, and $\lambda_2 = 0$ is the ratio between the total losses in an armour layer and the total losses in the corresponding conductor.

TABLE 1 Lower and upper bounds on the design variables

Design variable	Lower bound (m)	Upper bound (m)
W_2	$0.3 + 2{\cdot}d_2$	5
H	$0.245 + d_1 + d_2$	5
B	$(L_1 + d_1/2 + d_2 + 0.075)/2$	3.5
L_2	$L_1 + d_1/2 + d_2/2$	5
S_2	d_2	2

The values assigned to the design variables are restricted by several inequality constraints. Some of these constraints denote the lower and upper bounds for these variables. For instance, the upper bound for the cable bedding width represents the maximum available soil zone intended for the installation of cables, and the lower bound for the axial spacing between cables represents the outer diameter of one cable. The lower bounds for W_2 and H depend on the cable parameters, as well as the following requirements for underground cable lines [14]: (i) distances between the axes of two outer cables and the lateral sides of the cable bedding closest to them shall be not less than 0.15 m; (ii) height of the bedding-part below the cables shall be not less than 0.075 m, and (iii) height of the bedding-part above the cables shall be not less than 0.17 m. Assuming that the first line is installed in the ground at a constant depth L_1, and that the second line is installed below the first one, the lower bound for the laying depth of the second line L_2 will be equal to $L_1 + d_1/2 + d_2/2$. In connection with this, d_1 and d_2 represent the outer diameters of cables in the first and second line, respectively. Having this in mind, the lower bounds are set as design variables, while the upper bounds are assumed to be identical with those from [14]. These bounds are outlined in Table 1.

2.2 | Inequality constraints

Generally, the inequality constraints (Equation (2)) may be regarded as interrelationships between the design variables. Accordingly, for the case under consideration, the following inequality constraints are defined:

1. Depth of the cable bedding centre – Assuming that at least 0.17 and 0.075 m of bedding material is required above and below the cables, respectively, as well as assuming that the cable trench is completely filled with the bedding material to the level of the ground surface, the following constraints should be met:

$$L_1 - \frac{d_1}{2} - 0.17 + \frac{H}{2} > B > L_2 + \frac{d_2}{2} + 0.075 - \frac{H}{2}, \quad (8)$$

$$B \geq \frac{H}{2}. \quad (9)$$

2. Width of the cable bedding of the second cable line – Assuming that at least 0.15 m of bedding material is required on each side of the centres of two outer cables, the following constraint should be satisfied:

$$W_2 \geq 0.3 + 2S_2. \quad (10)$$

2.3 | Expanded objective function

In order to satisfy the inequality constraints (Equations (8), (9), and (10)), through a penalty factor, the objective function is defined. Now, the extended objective function that needs to be minimised becomes:

$$F_e = F(\boldsymbol{x}) + p \cdot \sum_{i=1}^{q} \left| x_i - x_i^{\lim} \right|, \quad (11)$$

where p is the corresponding penalty factor, q is the number of inequality constraints, and $x_i^{\lim}$ is an upper or lower bound on the design variable x_i. The bound $x_i^{\lim}$ can be expressed as:

$$x_i^{\lim} = \begin{cases} x_i^{\max} & \text{if} \quad x_i > x_i^{\max} \\ x_i^{\min} & \text{if} \quad x_i < x_i^{\min} \\ x_i & \text{if} \quad x_i^{\min} \leq x_i \leq x_i^{\max} \end{cases}, \quad (12)$$

where $x_i^{\max}$ and $x_i^{\min}$ are the upper and lower bounds on the design variable x_i, respectively. In addition, these bounds can be defined by constants or expressions.

The value for the penalty factor p is determined using the trial and error method, and in this case, it is fixed at 1000.

3 | A COMPUTATIONAL CASE STUDY ON THE CABLE CROSSING

The possibility of increasing the DF of underground power cables will be demonstrated on the crossing of two cable lines from Figure 1 as an example, that is, a case study. The first cable line is a 110 kV circuit consisting of three single-core cross-linked polyethylene (XLPE) insulated cables laid in flat formation, where the cables are regularly transposed and the metal screens are bonded at both ends of the cable line. These 110 kV cables have conductors and metal screens with cross-sectional areas of 800 and 100 mm², respectively. In order to illustrate the effect of different cross-sectional areas of the conductors and metal screens on the optimal solution, the optimisation procedure is carried out by considering the second cable line consists of 33 kV single-core XLPE-insulated cables: (i) with conductors and metal screens having cross-sectional areas of 95 mm² and 16 mm², respectively; or (ii) with conductors and metal screens having cross-sectional areas of 630 and 300 mm², respectively.

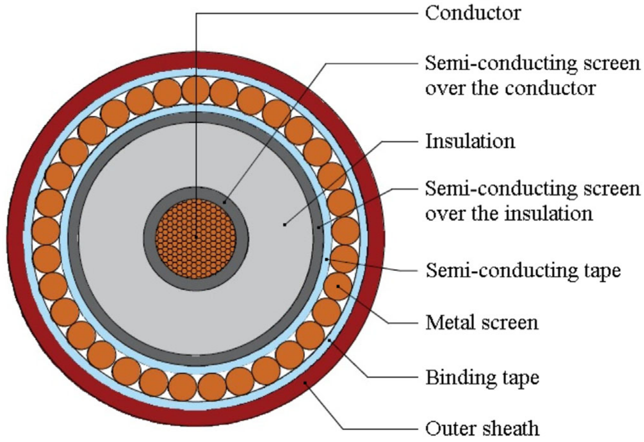

FIGURE 2 Construction elements of the 2XS(FL)2Y cable with a round multi-wire compacted conductor of Class 2 (according to IEC 60502-2:2005)

Moreover, the optimisation is carried out considering the following two bonding methods for the metal screens of the second cable line: (i) regular transposition of the cables where the metal screens are bonded at both ends of the cable line, and (ii) without transposition of the cables where the metal screens are bonded at both ends, with the central cable equidistant from the outer cables. These bonding methods are selected because their implementation is not expensive compared to the costs for conventional cross-bonding of the metal screens, regardless of the fact that the cross-bonding has greater applicability to the electrical distribution systems [15]. The cable construction used in the optimisation procedure is shown in Figure 2, while its elements are described in Table 2. The cable bedding material is a sand-bentonite mixture (SBM) composed of MX-80 (Na-bentonite), sand and water. Thermal resistivity of this SBM material is 1.05 Km/W [16].

In order to improve the conduction of heat away from the cables, it is assumed that the cables are installed in a cable bedding made of a well heat-conducting material. The rectangular cross-section of any cable bedding, having the dimensions x and y, can be modelled with an equivalent thermal envelope whose radius is [17,18]:

$$r_b = \exp\left[\frac{1}{2} \cdot \frac{x}{y} \cdot \left(\frac{4}{\pi} - \frac{x}{y}\right) \cdot \ln\left(1 + \frac{y^2}{x^2}\right) + \ln\left(\frac{x}{2}\right)\right] \quad (13)$$

where $x = \min(W, H)$ and $y = \max(W, H)$.

TABLE 2 Outer diameters, materials and thermal resistivity for construction elements of 33 kV and 110 kV cables which are represented by Figure 2

Construction element	Outer diameter (mm) 33 kV cables 95 mm^2	630 mm^2	110 kV cables 800 mm^2	Material	Thermal resistivity (Km/W)
Conductor	11.4	29.81	34.2	Copper	0.0025
Semi-conducting screen over the conductor	12.8	30.81	36.6	Semi-conducting XLPE	3.5
Insulation	28.8	46.81	76.6	XLPE	3.5
Semi-conducting screen over the insulation	30.8	48.81	79.0	Semi-conducting XLPE	3.5
Semi-conducting tape	32.6	50.41	81.1	Semi-conducting polyethylene	3.5
Metal screen / Number of wires	34.11 / 36	55.05 / 71	85.68 / 24	Copper	0.0025
Binding tape	35.86	57.1	88.0	Semi-conducting polyethylene	3.5
Outer sheath	40.26	65.1	96.0	High-density polyethylene	3.5

According to [3], when the two cable lines are inside the equivalent thermal envelope of radius r_b, the inclusion of the effect of thermal resistivity ρ_b (that differs from that of the native soil ρ_s) begins with the assumption that the thermal resistivity of all the material surrounding the cable lines inside the envelope is ρ_b. Then, in order to take into account the difference between the thermal resistivities of the envelope and of the native soil, a correction term is added algebraically to the relevant equation for the external thermal resistance of material surrounding the cables (see Equation (14)). In Equation (14), L is the cable laying depth, d_e is the outer diameter of one cable, and

$$T_4 = \frac{\rho_b}{2\pi}\left[\ln\left(\frac{2L}{d_e^2}+\sqrt{\left(\frac{2L}{d_e^2}\right)^2-1}\right)+2\ln\sqrt{\left(\frac{2L}{S_2^2}\right)^2+1}\right] + \frac{N}{2\pi}(\rho_s-\rho_b)\,G_b \tag{14}$$

$$G_b = \ln\left(\frac{B}{r_b}+\sqrt{\left(\frac{B}{r_b}\right)^2-1}\right) \tag{15}$$

is the corresponding geometric factor.

The replacement of the cable bedding of rectangular cross-section by the equivalent envelope having the same heat transfer capacity to dissipate heat losses is valid only for the ratio y/x lower than 3. In addition, when $B < r_b$, which is common in the case when the cable trench is filled with the cable bedding material up to or near the ground surface, the geometric factor G_b becomes a complex number that stops further calculation. To avoid this situation, the approximation $G_b \approx \ln(\frac{2\cdot B}{r_b})$ is used by some authors, which is not correct because B is not much larger than r_b for typical sizes of cable beddings and standard laying conditions. Because of the limitations mentioned, the geometric factor G_b is calculated using the table containing extended values of G_b for the external thermal resistance between cables in duct banks [19].

In order to evaluate the expanded objective function (Equation (11)), a dedicated computer code is developed in MATLAB/Simulink software package, where the particle swarm optimisation function (i.e. "particleswarm") from MATLAB's Global Optimization Toolbox is applied to minimise the objective function subject to the defined constraints. The PSO algorithm is described in [11] and often applied to the optimisation problems of this kind (maximisation of the cable ampacity and minimisation of the cable bedding costs). Pseudocode that solves the optimisation problem considered can be described by the following 14 steps:

1. Specifying the input parameters, such as outer diameters, materials and thermal resistivities from Table 2, ambient data, and bonding method for the second cable line.
2. Initialisation of a random population (group of particles) between the minimum and maximum values of the design variables W_2, H, B, L_2, and S_2.
3. Calculation of the dc resistance of the conductor and the ac resistance of the conductor and metal screen according to [13] for the second cable line.
4. Specifying the inequality constraints (Equations (8), (9), and (10)).
5. Calculation of the thermal resistance per phase between the cable conductor and metal screen and the thermal resistance of the outer sheath according to [20], as well as the external thermal resistance of the material surrounding the cables according to Equation (14) for the second cable line.
6. Calculation of the ampacity of the second cable line I_2 according to Equation (7), where the ratio λ_1 is calculated based on the ac resistance of the metal screen at its continuously permissible temperature (which is a function of the ampacity I_2). Therefore, an iterative procedure is required for the calculation in accordance with [13].
7. Calculation of the ampacity of the first cable line I_1 by repeating all the previous steps for the first cable line, with

the difference that the design variables are: $W_1 = 1.1$, H, B, $L_1 = 0.9$, and $S_1 = 2 \cdot d_1$.

8. Calculation of the derating factor for the second cable line DF_2 according to Equation (5), assuming that the ampacity I_1 flows through the conductors of the first cable line.
9. Calculation of the derating factor for the first cable line DF_1 according to Equation (5), assuming that the derated current $I_2 \cdot DF_2$ flows through the second cable line.
10. Calculation of the derating factor for the second cable line DF_2, assuming that the derated current $I_1 \cdot DF_1$ flows through the first cable line.
11. Repetition of the previous two steps for each cable line until there is no difference in calculating the derating factors.
12. Calculation of the value for the expanded objective function F_e (fitness function) using Equation (11)
13. Updating of all particles (elements of the vector of design variables).
14. If the termination criteria are met, then the PSO algorithm reports the optimal solution. Otherwise, the loop consisting of steps 2–13 will repeat itself.

Figure 3 shows a flowchart corresponding to the described pseudocode. The programme variables I_iter, eps, DF_1_iter and DF_2_iter, appearing in this flowchart, represent the auxiliary variables used to close the WHILE loops.

4 | RESULTS AND DISCUSSION

When a new cable line should cross the existing one, the depth of laying and axial spacing between the cables in the existing cable line (usually consisting of three single-core cables) cannot be significantly changed without cutting the cables and jointing them at the crossing area. Usually, at the crossing areas, to ensure a minimum depth of laying for high voltage (HV) cables and a certain vertical distance between the cable lines, new cable lines should be placed below the existing ones. For the areas where cables cross each other, there are no criteria for precisely defining the vertical distance between the cable lines. In some countries, the vertical distance between the planned underground line and the existing heat sources was already recommended as a minimum clearance distance. According to [3], this distance varies between 0.2 and 0.5 m.

For instance, in the calculation of the derating factor according to IEC 60287-3-3 standard, two cable lines crossing each other are installed at depths of 0.9 and 1.2 m. In addition to this, the axial spacing between three single-core cables in a flat formation is double the outer diameter of one cable. These values will be used as reference (that is, common) for the purpose of comparisons with the corresponding design variables obtained by applying the proposed optimisation procedure. In the example considered in IEC 60287-3-3, it is assumed that all the soils surrounding the cables are of uniform thermal conductivity. In this example, as illustrated in Figure 1, the cables are installed in the cable bedding which is surrounded by the native soil.

As can be seen from Table 3, the common values for the width and height of the cable bedding that encloses both cable

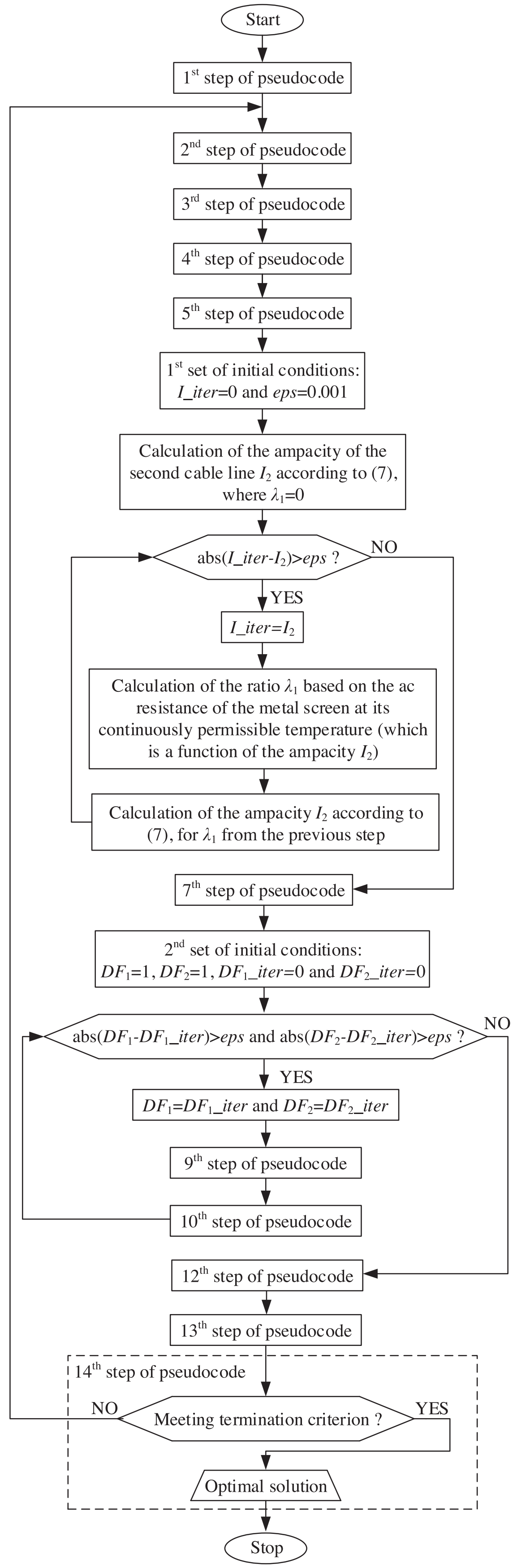

FIGURE 3 Flowchart of the proposed optimisation procedure

TABLE 3 A comparison of the results obtained for the common and optimal designs of considered cable lines in their crossing and the common designs of considered cable lines outside the cable crossing

	Cable designation: Conductor/metal screen cross-sectional area, rated voltage, bonding method	S (m)	W (m)	H (m)	B (m)	L (m)	I (A)	Derated current[a] (%)
Cable bedding size and design parameters of the first and second cable line outside the cable crossing	95/16 mm^2, 33 kV, RTC[b]	0.0805	1.1	0.5	0.745	0.9	277.35	0
	95/16 mm^2, 33 kV, NTC[c]	0.0805	1.1	0.5	0.745	0.9	280.51	
	630/300 mm^2, 33 kV, RTC	0.1302	1.1	0.5	0.757	0.9	508.73	
	630/300 mm^2, 33 kV, NTC	0.1302	1.1	0.5	0.757	0.9	489.03	
	800/100 mm^2, 110 kV, RTC	0.192	1.1	0.5	0.775	0.9	567.11	
Common values for the cable bedding size and design parameters at the crossing area[d]	95/16 mm^2, 33 kV, RTC	0.0805	1.1	0.8	0.9	1.2	231.48	−16.54
	800/100 mm^2, 110 kV, RTC	0.192	1.1	0.8	0.9	0.9	515.14	−9.16
	95/16 mm^2, 33 kV, NTC	0.0805	1.1	0.8	0.9	1.2	233.9	−16.61
	800/100 mm^2, 110 kV, RTC	0.192	1.1	0.8	0.9	0.9	514.02	−9.36
	630/300 mm^2, 33 kV, RTC	0.1302	1.1	0.8	0.9	1.2	438.2	−13.86
	800/100 mm^2, 110 kV, RTC	0.192	1.1	0.8	0.9	0.9	505.07	−10.94
	630/300 mm^2, 33 kV, NTC	0.1302	1.1	0.8	0.9	1.2	420.5	−14.01
	800/100 mm^2, 110 kV, RTC	0.192	1.1	0.8	0.9	0.9	503.14	−11.3
Optimal values for the cable bedding size and design parameters at the crossing area [d]	95/16 mm^2, 33 kV, RTC	0.5833	1.4667	1.7599	1.0559	1.8408	276.75	−0.2
	800/100 mm^2, 110 kV, RTC	0.192	1.1	1.7599	1.0559	0.9	610.09	7.58
	95/16 mm^2, 33 kV, NTC	0.5831	1.4662	1.7594	1.0556	1.8402	280.9	0.14
	800/100 mm^2, 110 kV, RTC	0.192	1.1	1.7594	1.0556	0.9	607.45	7.11
	630/300 mm^2, 33 kV, RTC	0.0651	1.4274	1.7129	1.0277	1.7766	510.84	0.41
	800/100 mm^2, 110 kV, RTC	0.192	1.1	1.7129	1.0277	0.9	610.77	7.7
	630/300 mm^2, 33 kV, NTC	1.2550	2.8099	1.7562	1.0537	1.8243	578.78	18.3
	800/100 mm^2, 110 kV, RTC	0.192	1.1	1.7562	1.0537	0.9	589.12	3.88

[a]For any of the two crossing cable lines, the derated current represents the percentage difference between the ampacity that takes into account the negative thermal effects of the cable crossing (for the common or optimal thermal environment and design parameters) and the ampacity that corresponds to the design of the same cable line outside the cable crossing. The ampacities are compared to each other based on the same cross-sectional areas of the conductors and the same bonding methods of the metal screens. Accordingly, positive values mean that there is no hot spot effect in the crossing area and vice versa.

[b]RTC – in the case where regular transposition of the cables is carried out together with the bonding of the metal screens at both ends of the cable line.

[c]NTC – in the case where no transposition of the cables is carried out together with the bonding of the metal screens at both ends of the cable line.

[d]In these two rows of the table, the horizontal solid lines subdivide the data into data sets corresponding to the pairs of power cables that cross each other.

lines at the crossing area are 1.1 m and 0.8 m, respectively. The value of 1.1 m corresponds to the optimal width of the cable bedding for the case of laying HV single-core cables in flat formation from [21], which is also in line with the values from [14]. The cable bedding height of 0.8 m is obtained by considering the height of the bedding-part below the lower cable line equals 0.1 m, and the height of the bedding-part above the upper cable line equals 0.4 m in relation to the axes of the cables; which is in accordance with [21] and [14]. Accordingly, the height of the bedding-part between the two cable lines is 0.3 m. For the first and second cable lines outside the cable crossing, the optimal height of their cable beddings is 0.5 m, while the ratio between the heights of the bedding-parts below and above the cables is the same as in the crossing area.

The values for the cable ampacities corresponding to the crossing area (for the common or optimal thermal environment and design parameters) and the common designs of considered cable lines outside the cable crossing are given in Table 3. The difference between these ampacities represents the derated current, i.e. the value for which it is necessary to reduce the ampacity of the corresponding cable line in order to avoid overheating of its cables in the crossing area. This difference, expressed as a percentage, in the case of common values for the cable bedding size and design parameters of the corresponding cable line, ranges between −9.16% and −16.61%. On the other hand, in the case of optimal values for the cable bedding size and design parameters (obtained by the proposed optimisation procedure), the difference is positive, except in one case (when the difference is −0.2%). It means that, by optimising the thermal environment and design parameters, the electricity transmission bottleneck can be mitigated or eliminated at the cable crossing. Moreover, it should be noted that the common (rated) transmission performance of the existing 110 kV cable line (for which it is designed) is not reduced in this particular case. This is very important because it was expected as the main result of the proposed optimisation procedure.

Based on the performed optimisation procedure, it can be said that a slightly greater derated current can be expected for the cables having smaller cross-section areas of the conductors and metal screens. In addition, the cables having a smaller cross-section area of the metal screens are not sensitive to the type of bonding method, so the optimal axial spacing between the cables is almost the same for both bonding methods considered. On the other hand, in the case where there is regular transposition of the cables, if the metal screens with a larger cross-section area are bonded at both ends, then the optimal axial spacing between the cables is minimal. Whilst, in the case where there is no transposition of the cables, this spacing becomes significantly greater (1.255 m). This is not in accordance with expectations, because by increasing the axial spacing between the cables, circulating currents increase. Thus, it is logical that the cables should be brought closer together in the cable bedding. However, the algorithm has found that reducing the mutual thermal effects of adjacent cables when separating heat sources from each other has a more favourable effect on the cable ampacity than reducing circulating currents (Joule losses) when heat sources are approaching each other.

The mentioned two bonding methods are considered because it appears that in practice they are quite frequently used for three single-core cables in flat formation at voltages below 66 kV [22]. In the case when there is no transposition of the cables, the ampacity of the hottest (central) cable in the second cable line is calculated based on the value for λ_1, which is obtained using the formula for the outer cables. In this manner, the value of λ_1 is significantly higher than that which would be obtained by applying the formula for the central cable.

According to [3], a distance between the hottest point in the crossing area (the conductor of the central cable) and a point where a longitudinal heat flow is negligible equals 6 m. Accordingly, the cable bedding of the optimal size should be applied along a 12 m length of each of the two cable lines crossing each other. For the crossing area, the volume (amount) of cable bedding material and excavation costs are lower in the case of common bedding size than in the case of optimal bedding size. However, this difference in one-time costs is not significant compared to the potential long-term benefits due to the increases in the ampacities of both cable lines.

The cable ampacity is calculated assuming that the load factor m equals 1 (i.e. 100%), that the ambient conditions are the same as in Figure 1, and that the cable lines cross each other at an angle of 90° (the second cable line is perpendicular to the first one). Based on the results of the analysis carried out, it is found that the voltage levels and crossing angle (which is not lower than 30°) of the two cable lines do not significantly affect the cable ampacity, optimal bedding size, and optimal design parameters. Based on the same results, it is confirmed that the lower zone of the cable bedding represents the best possible location for the cables in terms of heat transfer capacity to dissipate heat losses. This is in accordance with the observations reported in [14, 21, 23].

The results presented in Table 3 are based on the assumption that the cable bedding material at the crossing area and along both cable routes is the same (with $\rho_b = 1.05$ Km/W in the case of the drying-out of the cable bedding). In addition, it is also assumed that the entire area surrounding the cable bedding is completely dried out and that the thermal resistivity of this area is $\rho_s = 2.5$ Km/W. In practice, a material with a lower thermal resistivity (for instance, a fluidized bedding material whose thermal resistivity is 0.65 Km/W) may be used for the cable crossing areas, and the native soil surrounding the cables may not be completely dried out. Therefore, all the obtained results can be regarded as extremely optimistic.

A PSO-based optimisation of the case where the metal screens are cross-bonded was not considered because, in general, the currents flowing through them are equal to zero or negligibly small. This was the main reason why the PSO algorithm kept trying to separate the cables from each other in order to find the optimal steady-state solutions. Based on this, it is obvious that the separation has a greater effect on the objective function than any increase in the costs for cable bedding. In addition to the PSO algorithm, the other metaheuristics, such as genetic algorithm (GA), gravitational search algorithm (GSA), simulated annealing algorithm (SAA), etc., were also tested. Each run of the PSO algorithm provided very similar results, while, for instance, the results obtained by rerunning the GA and GSA differed from each other by several dozen percent. These differences were even greater for comparisons between the mentioned methods and some other metaheuristics. Therefore, the results obtained when comparing the PSO algorithm to other optimization methods were not presented in this paper.

Moreover, dynamic models of heat transfer can be used to solve such optimisation problems. The dynamic models require the "cable loading history" and current environmental conditions, which are stochastic, highly variable, and difficult to predict or estimate accurately. In addition to this, it is unclear what would be the benefits of dynamic thermal analysis of cables in terms of the reduction of their lifespans. In practice, the dynamic heat transfer models have little or insignificant application in the design stage of underground cable lines, where all calculations should be carried out under the assumption of steady-state constant load operation. Accordingly, the application of dynamic heat transfer models in the design stage of underground cable lines can only be considered theoretically.

5 | CONCLUSION

According to the results obtained, in the design stage of a new cable line crossing existing heat sources, the proposed optimisation procedure can be used for optimal designing of the cable bedding and determination of the optimal positions for the cables of one new cable line inside that cable bedding. This is in order to avoid overheating of the cables and prevent the cables from premature damage. It was shown that, in the crossing area, the optimal solution is achievable with minimal consumption of the cable bedding material and without the use of additional cooling equipment. The PSO algorithm was successfully applied to minimise the objective function. In addition, the PSO algorithm proved to be highly stable in terms of converging to the same solutions after the calculations were run several times. The number of iterations that were considered for the purposes of the PSO optimisation was 350.

It was found that the vertical distance between the considered cable lines in the crossing area should be about 0.9 m, which is significantly larger than the distance usually applied in practice (about 0.3 m). For the optimal values of the cable bedding size and design parameters at the crossing area, the results showed that it is possible to achieve an increase in the ampacity for each of two cable lines by about 15% on average, with respect to the case of common design parameters that are traditionally applied to the cable crossings. In addition, it was established that, in relation to the parts of the cable lines outside the cable crossing, the increase in the cable ampacities is sufficient to avoid electricity transmission bottlenecks (at the crossing area). The increase was successfully validated by the considered case study. It was also found that, for exact values of the derated currents, it is necessary to know data on both cable lines crossing each other, such as cable constructions, native soil properties, bedding properties, and laying parameters for the cable route parts outside the crossing. Finally, the effects of the cross-sectional areas of the conductors and metal screens and the metal screen bonding methods on the optimal solution were identified and quantified adequately. In this context, the optimal solution corresponds particularly to the axial spacing between the cables.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs.

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