Research on Optimum Laying Method for Increasing Underground Power Cable Ampacity

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Abstract. When the cables are laid with equal spacing, its ampacity is limited due to the mutual heat effects. In order to increase the ampacity of the cable group, an optimum laying method with unequal spacing is proposed in this paper. The constraint function is that the temperature of all cables is lower than the upper limit, and the objective function is that the ampacity of cables is maximum. The constrained problem is transformed to an unconstrained problem by constructing a penalty function. The results show the effectiveness of the proposed method. The ratio of the increased ampacity increases with the increase of cable numbers.

1. Introduction
When power cable is running, the components of core, insulating layer and sheath will generate heat due to loss, which will increase the temperature of each part of the cable. For XLPE insulated cables, the current carrying capacity corresponds to the constant load current at 90 °C of core temperature. Current carrying capacity is an important parameter in cable design and operation. Constant load current above current capacity will shorten cable life and reduce operational reliability. Below the current capacity, cable transmission capacity cannot be fully utilized. [1-4]. The IEC-60287 standard provides a current-carrying calculation formula for a direct-buried cable, which is highly accurate for soils with uniform thermal conductivity. [5]. When the cables are laid in clusters, the mutual heat effect will result in high temperature rise of cables in the central region and low temperature rise of cables in the edge region if the equal spacing is adopted. The difference in temperature rise will result in low utilization rate of edge cables, thereby limiting the overall transmission capacity of cable clusters. In order to solve this problem, the artificial fish swarm algorithm is used to arrange the cables with unequal spacing. The spacing of cables from the centre to the edge decreases from large to small, which reduces the mutual heat effect of the central cables and increases the mutual heat effect of the edge cables, and reduces the temperature difference of the cable cores at different locations, so as to improve the current carrying capacity of the cable cluster. In order to better reflect the advantages of unequal spacing arrangement of cables, this paper uses IEC method to calculate and compare the carrying capacity of multi-loop cables laid with medium spacing and optimized with unequal spacing in uniform soil.

2. Calculating Method of Ampacity of Power Cable Cluster
IEC-60287 gives the formula for calculating the current carrying capacity of directly buried AC cables as follows:
\[ I = \sqrt{\frac{(\theta_{\text{max}} - \theta_c) - W_d}{\frac{0.5T_1+T_2+T_3}{\lambda_1}} + \frac{n(T_2 + T_3 + T_4)}{\lambda_2}}} \]  

In the formula, \( I \) is the current in the cable, \( \theta_{\text{max}} \) is the maximum working temperature for the cable, \( ^\circ \text{C} \); \( \theta_c \) is the ambient medium temperature, \( ^\circ \text{C} \); \( W_d \) is the dielectric loss of the insulation layer per phase of the cable, W/m; \( T_1 \), \( T_2 \), \( T_3 \), \( T_4 \) are thermal resistance of insulating layer, insulation shielding, outer shield and surrounding medium; \( R \) is the unit length resistance of each phase of cable core, \( \lambda_1 \) and \( \lambda_2 \) are the ratio of metal sleeve loss and cable armor loss to core loss, respectively.

If \( N \) identical cables are laid in the soil and the load current is the same, the mutual heat effect between cables should be considered. The equivalent thermal resistance \( T_d \) of the K-th cable around the cable is obtained by the mirror method [6].

\[ T_d = \rho T_4 \frac{\ln \left( \frac{4L}{D_c} \times \frac{d_{1K}}{d_{2K}} \times \frac{d_{3K}}{d_{4K}} \times \cdots \times \frac{d_{NK}}{d_{NK}} \right)}{2 \pi} \]  

where \( \rho T_4 \) is the thermal resistance coefficient of the soil, \( K \cdot \text{m} / \text{W} \); \( L \) is the laying depth of the cable, m; \( D_c \) is the outer diameter of the outer sheath of the cable, m; \( d_{1K}, d_{2K}, \cdots, d_{NK} \) are respectively cable 1, 2, ..., the distance from the center of \( N \) to the center of the cable, m; \( d'_{1K}, d'_{2K}, \cdots, d'_{NK} \) are the distances from the mirror center of the cable 1, 2, ..., \( N \) to the center of the cable K, respectively.

3. Cable Group Optimization Based on Artificial Fish Swarm Algorithm

3.1 Mathematical Model

The cable cluster is laid in the way of Fig. 1, and A, B, and C indicate the three-phase and the lower-angle standard circuit number of each circuit. In this paper, the Artificial Fish Swarm Algorithm (AFSA) is used to find the optimal laying position of the cable [7]: The cable cluster current \( I \) and the core operating temperature \( \theta_i \) and the cable laying position coordinates \( [x, y] \) are variables, and \( I_{\text{max}} \) is the objective function. The constraint conditions are: 1), the operating temperature of each cable core is lower than the maximum allowable value of 90° C; 2), the adjacent two loop cable spacing is not less than the cable outer diameter, that is, the horizontal coordinate of each loop is greater than the previous loop abscissa. The sum of the outer diameters of the cables. This problem can be described by equations (3) to (4):

\[ \text{Objective function: Max} \ I = f(x, y) \]  

\[ \begin{align*}
\theta_i & \leq 90^\circ \text{C} \\
0 & \leq x_j \leq \text{width}
\end{align*} \]  

**Figure 1.** Map of laying for identical and single-core cables

where \( m \) is the number of loops in a single-core cable cluster, \( N \) is the total number of cable clusters, \( D_c \) is the outer diameter of the cable, \( \text{width} \) is the laying width of the cable group. This problem
assumes that the four boundaries of the section of the cable cluster laying area are fixed, and the x-coordinates of the three-phase cables per loop are the same, so the main work is to use the artificial fish swarm algorithm to determine the optimal coordinates of the x-direction of each loop.

![Calculation flowchart of power cables collocation optimization based on AFSA](image)

**Figure 2.** Calculation flowchart of power cables collocation optimization based on AFSA

### 3.2 Processing of Constraints

In this paper, the penalty function method is used to construct a generalized objective function with penalty terms, and the constrained problem is transformed into an unconstrained problem [8].

Abstract mathematical model:
where \( h_1(x), h_2(x) \) and \( h_3(x) \) are functions constructed using constraints. The out-of-bounds constraint of the inequality constraint is added to the objective function \( f(x) \) in the form of a penalty term, and the fitness function (i.e., the penalty function) \( F(x) \) of the artificial fish swarm algorithm is constructed:

\[
\text{Min } F(x) = -f(x) + c_i \sum_{i=1}^{3} H_j(x)
\]

where the second term in the right is the penalty term, the penalty coefficient \( c_i \) is greater than zero and decreases as the number of iterations increases.

The program flow of the cable group optimization design based on the artificial fish swarm algorithm is shown in Figure 2.

4. Optimization Layout Calculation Results Analysis

The calculation object is YJLW03 64/110 kV power cable. Tab. 1 shows the cable structure parameters. The soil thermal resistance coefficient is 1.0K·m/W, and the original soil temperature in the laying area is 20 °C. Tab. 2 shows the cable core temperature, circuit spacing and current carrying capacity after equidistant laying and optimized placement.

**Table 1. Structure parameters of the power cable**

| Cable structure Parameter | Conductor diameter /mm | Appropriate thickness of water blocking layer /mm | Conductor shielding thickness /mm | Wrinkle aluminum sleeve thickness /mm | Insulation thickness /mm | Outer layer thickness /mm | Insulation shielding thickness /mm | Cable outer diameter /mm |
|--------------------------|------------------------|-----------------------------------------------|---------------------------------|--------------------------------------|-------------------------|------------------------|-------------------------------|------------------------|
| Thermal resistance coefficient/((K·m)·W⁻¹) | 30.3 | 0.0025 | Conductor diameter /mm | 1.3 | 3.5 | Conductor shielding thickness /mm | 16.5 | 3.5 | Insulation thickness /mm | 1.0 | 3.5 | Insulation shielding thickness /mm | 2×1.5 | 6.0 | Parameter | 2.0 | 0.0042 | Outer layer thickness /mm | 5.5 | 3.5 | Cable outer diameter /mm | 99.1 | — |

It can be seen from Tab. 2 that the cables are equally spaced, the average cable core temperature is 83 °C, the temperature of the middle cable core is obviously higher than that of the edge cable, and the maximum temperature difference can reach 17 °C. After optimal placement, the average core temperature increased to 87 °C and the maximum temperature difference was reduced to 6 °C. For XLPE insulated cables, the difference between the core temperature and 90 °C reflects the current carrying capacity of the cable to be excavated. The closer the average temperature is to 90°C, the higher the overall utilization rate of the cables is. In Fig. 1, the optimal layout of the 7-loop cable is 5.8% higher than that of the equal-pitch arrangement. Fig. 3 shows the improvement of the current carrying capacity of the optimal arrangement than the equidistant laying when the cable group circuit number \( m \) is increased according to the method of Fig. 1. When the number of circuits is greater than 3, the transmission capacity of the optimized laying increases with the number of circuits, and the unequal spacing optimization technology makes more sense for multi-loop cable cluster laying.
Table 2. Comparison of Ampacities and core temperatures between equal and unequal spacing

| Number of loops | 1  | 2  | 3  | 4  | 5  | 6  | 7  | Vertical spacing /mm |
|-----------------|----|----|----|----|----|----|----|-----------------------|
| Equal spacing   |    |    |    |    |    |    |    |                      |
| Core Temp. /℃   | A  | 73 | 80 | 83 | 84 | 83 | 80 | 73 | 0                    |
|                 | B  | 78 | 85 | 89 | 90 | 89 | 85 | 78 | 193                  |
|                 | C  | 77 | 84 | 87 | 88 | 87 | 84 | 77 | 193                  |
| Circuit spacing /mm | 0  | 233| 233| 233| 233| 233| 233| —                      |
| Ampacity /A     |    |    |    |    |    |    |    | 446                   |
| Unequal spacing |    |    |    |    |    |    |    |                      |
| Core Temp. /℃   | A  | 84 | 87 | 87 | 86 | 87 | 87 | 84 | 0                    |
|                 | B  | 87 | 90 | 90 | 89 | 90 | 90 | 87 | 93                   |
|                 | C  | 84 | 87 | 87 | 88 | 87 | 87 | 84 | 293                  |
| Circuit spacing /mm | 0  | 100| 240| 360| 360| 240| 100| —                      |
| Ampacity /A     |    |    |    |    |    |    |    | 472                   |

Figure 3. The increased rate of ampacity as a function of the number of loops

5. Conclusion
(1) Adopting equal spacing arrangement, the mutual heat effect between cables makes the central cable of the cable cluster hot, while the edge cable of the cable cluster cold.
(2) Unequal spacing arrangement of cable spacing is gradually reduced from the center to the edge of the cable cluster, which can reduce the temperature difference of the entire cable cluster core.
(3) Unequal spacing arrangement of cable clusters excavates the conveying capacity of edge cables and improves the transmission capacity of cable clusters.

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