Method for Raising Load Capacity of Underground Cable Line

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Abstract. An optimized method for calculating the maximum current loadings of underground cables are developed based on the International Electrotechnical Commission (IEC) standard. Increasing the load of lateral cable and at the same time reducing the inside cable’s load, with the temperature of every cable lower than maximum permissible temperature as a constraint condition and taking the maximum sum of total current as objective function. The optimal operation value of each loop is calculated by the barrier function method and the improved Newton’s method is used to calculate the maximum value of current. The results reveal that this method can improve the total current of the cable by 5% greater than standard ampacity method and the effect is better in the case of multi loop, exploring the load potential of existing cable lines effectively and improving the economy of the cable.

Introduction

With the importance of power cable in urban power grid, it is a concerned issue for people to improve the safety of cable operation and reduce the cost of use. Accurate calculation of current carrying capacity is a prerequisite for safe and efficient operation of cables. There are two kinds of methods to determine the ampacity of cables: analytical calculation and numerical calculation. The advantages of analytical calculation method are simple, quick and easy to implement, the problem is that it is more suitable for the calculation of simple working conditions [1,2]. However, the numerical method it is more effective to solve the cable flow under complex conditions. In this paper, the optimization of the operation of cable group is studied by using homogeneous soil as the premise, so as to improve the transmission capacity of existing cable lines.

An Analytical Method for Calculating the Ampacity of Cable Group

Analytical calculation of steady flow of cable group usually uses relevant standards given by IEC60287:

\[
I_i = \frac{(\theta_i - \theta_c) - W_d(i)(0.5T_{w} + n(T_{u} + T_{o} + T_{s}))}{R_iT_u + nR_i(1 + \lambda_1)T_{w} + nR_i(1 + \lambda_1 + \lambda_2)(T_{s} + T_{o})}
\]  

(1)

Where \(I_i\) is the cable load current of number \(i\), A; \(\theta_i\) correspond to the temperature of cable core, °C; \(\theta_c\) is the temperature of Laying soil, °C; \(W_d(i)\) is the dielectric loss per unit length of cable insulation, K/m; \(R_i\) is the AC resistance of cable core unit length at the temperature of \(\theta_i\), Ω/m; \(n_i\) indicates the number of conductors in the cable loaded; Thermal resistance per unit length between single cable core and metal sheath, K • m/w; \(T_{w}\) indicates the thermal resistance per unit length, K • m/w; \(T_{o}\) indicates the thermal resistance per unit length, K • m/w; \(T_{s}\) indicates the unit length resistance between single cable surface and surrounding medium, K • m/w; \(\lambda_1\), \(\lambda_2\) indicates the ratio of the loss of the cable metal sheath and the loss of the sheath to the heat loss of all conductors of the cable respectively.
Each cable is used as an independent heat source when the cable is laid, the mutual influence between each other makes the temperature superposition, If the cluster has \( N \) root cable, The superposition of other \( N-1 \) cable thermal effect can be understood as the ambient temperature rise of the \( i \)-th cable. The following relations can be obtained[3-5]:

\[
I_i = \frac{(|\theta_i - \theta| - W_{ij}(0.5T_{ij} + n(T_x + T_u + T_j)) - \Delta \theta_{sat}}{\sqrt{R(I_j + R_{ij})T_x + nR(1+\lambda_j)T_u + T_{ij})}}
\]

\[
\Delta \theta_{sat} = \sum_{j \neq i} n_j(I_j^2R_j(1+\lambda_{ij} + \lambda_{ji}) + W_{dj}) \frac{\rho_s}{2\pi} \ln \frac{d_{ij}}{d_y} \tag{2}
\]

Where \( \Delta \theta_{sat} \) indicates the effect of other cable cooling on the ambient temperature of \( i \)-th cable,\(^\circ\)C; \( I_j \) is the load current of \( j \)-th cable, A; \( W_{dj} \) indicates the insulation dielectric loss per unit length of \( j \)-th cable, K/m; \( R_j \) is the AC resistance of \( j \)-th cable core unit length at the temperature of \( \theta, \Omega/m \); \( n_j \) indicates the number of cable core with current in cable,\( \lambda_{ij}, \lambda_{ji} \) indicates the ratio of the loss of the cable metal sheath and the loss of the sheath to the heat loss of all conductors of the cable respectively.\( d_{ij} \) indicates the distance between cable \( i \) and cable \( j \), m; \( d_{ij}' \) indicates the mirror distance between the center of \( i \) cable and \( j \) cable, m; \( \rho_s \) indicates the coefficient of thermal resistance of soil, K \( \cdot \) m/W.

**Optimization Method for Raising the Overall Transmission Current of Cable Group**

**Constraint Conditions and Optimization Objectives of Computational Methods**

In this paper, the constraint condition of the problem is that the highest of the cable core temperature of a single cable is not more than 90\(^\circ\)C, and the optimization target is the maximum transmission current of the cable group. If \( I_i \) represents the \( i \)-th cable current and \( \theta \) indicates the cable core temperature, the relationship will be obtained by the following:

\[
\text{Max} \ f_s(x) = I_1 + I_2 + \cdots + I_n \tag{4}
\]

\[
\theta_i \leq 90, i = 1, 2, \cdots, n. \tag{5}
\]

The formula (4) as the objective function, the formula (5) is the constraint.

**Realization of Constraint**

The internal penalty function method is used in this paper, and the internal penalty function of the method is based on the common logarithmic barrier function. The temperature of the cable core increases with the increase of the current, and the relationship between them is nonlinear, the constraint condition of the problem can be transformed from the temperature relation into the current relation by the formula (2), so as to simplify the problem and get following formula:

\[
I_i^2 \leq (|\theta_i - \theta| - W_{ij}(0.5T_{ij} + n(T_x + T_u + T_j)) - \Delta \theta_{sat})/\sqrt{\sum_{j \neq i} n_j(I_j^2R_j(1+\lambda_{ij} + \lambda_{ji}) + W_{dj}) \frac{\rho_s}{2\pi} \ln \frac{d_{ij}}{d_y}}
\]

\[
\lambda_{ij}(T_x + T_u) - \frac{\rho_s}{2\pi} \sum_{j \neq i} n_j(R_j(1+\lambda_{ij} + \lambda_{ji}) + W_{dj}) \frac{d_{ij}}{d_y} / [\sum_{j \neq i} n_j(I_j^2R_j(1+\lambda_{ij} + \lambda_{ji}) + W_{dj}) \frac{\rho_s}{2\pi} \ln \frac{d_{ij}}{d_y}]
\]

The formula can be simplified to the following expression:
\[
\begin{align*}
\frac{c_{11}}{d_1} I_1^2 + \frac{c_{12}}{d_1} I_2^2 + \cdots + \frac{c_{1n}}{d_1} I_n^2 & \leq 1 \\
\frac{c_{21}}{d_2} I_1^2 + \frac{c_{22}}{d_2} I_2^2 + \cdots + \frac{c_{2n}}{d_2} I_n^2 & \leq 1 \\
& \vdots \\
\frac{c_{n1}}{d_n} I_1^2 + \frac{c_{n2}}{d_n} I_2^2 + \cdots + \frac{c_{nn}}{d_n} I_n^2 & \leq 1
\end{align*}
\]  \hspace{1cm} (7)

Further simplification can be obtained:

\[
f_i(x) = \frac{c_{i1}}{d_i} I_1^2 + \frac{c_{i2}}{d_i} I_2^2 + \cdots + \frac{c_{in}}{d_i} I_n^2 - 1 \leq 0, \ i = 1, 2, \ldots, n
\]  \hspace{1cm} (8)

According to the conventional algorithm in the penalty function method, the inequality constraints and objective function are combined, assumed [7, 8]:

\[
\phi = -\sum_{i=1}^{n} \ln(-f_i(x)) \quad (t > 0, f_i(x) < 0, i = 1, 2, \ldots, n)
\]

\[
\Rightarrow \min \left( f_0(x) - \sum_{i=1}^{n} \frac{1}{t} \ln(-f_i(x)) \right) = \min \left( f_0(x) - \frac{1}{t} \phi(x) \right)
\]  \hspace{1cm} (9)

In the formula: \( \phi(x) \) as barrier function; \( 1/t \) is penalty factor; \( 1/t \phi(x) \) for penalty term.

**Calculation Program**

The specific implementation measures of this paper are: using the penalty function method to solve the optimization problem; Optimization calculation of unconstrained problem is realized by the improved Newton method [6, 7]. The realization of the process is shown in Figure 1-2.

In Figure1 and Figure2: \( n \) is the cable number; \( 1/t \) as the penalty factor, \( 1/t(0) \) is the initial value of \( 1/t \); \( t_{in} \) indicates the attenuation factor; \( V \) is the gradient; \( V^2 \) for the Hessian operator; \( \alpha, \beta \) is the correction coefficient required for the calculation; \( e_{in}, e_{out} \) is used to control the accuracy, norm is the range of calculation function; \( x \) indicates the current for the previous cycle, \( x^* \) indicates the current value is updated after each cycle, \( \Delta x \) is the increment of current after single cycle. The inner penalty function method is used to solve the optimization problem. The improved Newton method of internal circulation is used to solve \( \text{Min}(f_0(x) + 1/t\phi(x)) \).

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**Figure 1.** Flowchart of barrier method.  \hspace{1cm} **Figure 2.** Frame of Newton’s Method.
Analysis of Optimization Algorithm

Calculation conditions are as follows: The cable adopts 110kV 400mm² single core XLPE power cable; directly buried installation, the parameters of soil take 20°C and thermal resistance coefficient take 1.0 K · m / W. The method of laying as shown in Figure 3, A/B/C represents the phase sequence of each loop cable, subscript indicating loop order. The ampacity of the cable group and the calculated values of the current and temperature are shown in Table 1.

Table 1. Comparison of ampacity and optimal currents and single core cables’ core temperature.

<table>
<thead>
<tr>
<th>parameter</th>
<th>Loop number</th>
<th>Sum of current of cable group/A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Formula method</td>
<td>A</td>
<td>74.2</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>78.4</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>78.0</td>
</tr>
<tr>
<td>current-carrying capacity/A</td>
<td></td>
<td>371.0</td>
</tr>
<tr>
<td>Optimization algorithm</td>
<td>A</td>
<td>83.9</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>90.0</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>89.1</td>
</tr>
<tr>
<td>Optimal current/A</td>
<td>500.1</td>
<td>383.0</td>
</tr>
</tbody>
</table>

As can be seen in table 2, under the optimized mode, the cable outside the cable group can carry more current due to its good heat dissipation condition; the cable in middle position should be reduced current properly due to its poor heat dissipation condition. The total current of the optimized cable group is nearly 5% higher than that of carrying capacity as control mode.

Conclusion

The optimization method proposed in this paper is based on the laying method of cable group, improving the current carrying of peripheral cable and reducing the current value of the intermediate cable Properly to realize the temperature of the cable core of the cable group is similar and reduce the difference between the average temperature of the cable core and 90°C, achieve the goal of improving the power transmission capacity of the cable group.

Reference


