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Optimal Planning Method of Distribution Transformer Network for Seasonal Load

Optimal Planning Method of Distribution Transformer Network for Seasonal Load

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Abstract. Taking into account the reliability of power supply, this paper proposes an optimal planning method for distribution transformer network adapting to seasonal load in order to improve the low efficiency of equipment utilization in rural coal-to-electricity conversion areas. In this method, a bi-level programming model of distribution transformer network is constructed to minimize the overall cost. Voronoi is used to plan the distribution transformer at the upper level, Prim algorithm is used to plan the low-voltage power supply line at the lower level, and genetic algorithm is used to optimize the solution (seek the optimal solution). Finally, the feasibility of this method is verified by the planning of distribution transformer in typical power supply areas. The analysis of examples shows that the distribution transformer loss can be reduced by establishing the low-voltage tie-line between distribution transformers and the transformation of operation mode, which also provides the basis for the load transfer under the low-voltage line fault.

1. Introduction

Recently, the state has put forward the beautiful countryside plan to promote rural development[1], and has successively implemented a number of special rural power grid projects, such as accelerating the upgrading of power grids in small towns', well power supply', household power supply, village power supply, and coal-to-electricity heating project[2]. The utilization rate of equipment and the economy of power supply have been greatly reduced after grid-connected operation because of the strong seasonality[3] of agricultural irrigation and electric heating. Therefore, using load complementarity and operation flexibility is of great significance to study the methods to improve the operation efficiency of distribution transformer network and optimize the planning [4-6] to support the sustainable development of power supply enterprises.

In order to improve the equipment utilization efficiency, reduce the loss and take into account the reliability of power supply in rural coal-to-electricity conversion areas, this paper presents an optimal planning method for distribution transformer network adapted to seasonal load. The main idea is to design a distribution transformer network and establish a low-voltage tie-line between distribution transformers. According to the seasonal load characteristics, some distribution transformers can be withdrawn from operation in low-load season by changing the state of the tie-line switch and changing the operation mode. During this, the problem of fault load transfer was solved and the reliability of rural power grid was improved. This method was divided into two stages to plan the distribution transformer network. In the first stage, the capacity location of the transformer was planned, and the Voronoi diagram was used to form the power supply range and the transformer low-voltage side tie-line adapted to seasonal operation mode conversion. In the second stage, the low-voltage power supply network was optimized according to the prim algorithm. Then, the simulation of the whole year was carried out. The optimal scheme was obtained by minimizing the cost of life cycle. This method provides a new way of thinking for the development of power grid in coal-to-electricity conversion area. It is conducive to reducing no-load loss, achieving the dual purpose of improving power supply reliability and economy. Besides, it has important significance for promoting enterprises and maintaining sustainable development.

2. Bi-level optimal planning model for distribution transformer network

2.1. Upper model: distribution transformer planning based Voronoi

Firstly, taking the capacity and location of distribution transformer as variables, a distribution transformer planning model with the objective of minimizing the comprehensive cost is constructed. In the iteration solution of the model, for a transformer site selection and capacity determination scheme, according to the geographical relationship between load and substation, Voronoi diagram method is used to divide the power supply range of transformer, and then considering the change of seasonal load operation mode, the tie lines between distribution transformers are laid out. Finally, combined with the low-voltage line planning scheme returned from the lower layer, large load season and small load season are adopted. Different operation modes are simulated for the whole year and the total cost is calculated. The optimal scheme with the minimum total cost is obtained through multiple optimization iterations.

2.1.1. Optimal planning model of distribution transformer based on minimum total cost

The total cost of distribution transformer network planning includes the investment cost of distribution transformers, low-voltage lines and transformer low-voltage tie-lines, and the operation and maintenance cost including maintenance and loss. Considering the time value of funds, the total cost calculation formula is as follows:

$$\begin{cases} \min C = \alpha C_{\mathrm{IV}} + C_{\mathrm{OPE}} \\ \alpha = \dfrac{\tau}{1-(1+\tau)^{-T_P}} \\ C_{\mathrm{IV}} = C_{\mathrm{T}} + C_{\mathrm{CON}} + C_{\mathrm{LL}} \end{cases} \tag{1}$$

The total cost of distribution transformer network planning includes: C_{IV} is the investment cost of system construction; C_{OPE} is the operation and maintenance cost; τ is the bank interest rate, T_{P} is the whole life cycle, and α is the equivalent annual coefficient of equipment; C_{T} is the construction cost of distribution transformers; C_{CON} is the construction cost of tie-lines between distribution transformers; C_{LL} is the construction cost of low-voltage lines, and by lower model calculation.

The formulas for calculating each component of investment cost are as follows:

$$\begin{cases} C_{\mathrm{T}} = \sum_{i=1}^{N_{\mathrm{T}}} C_{\mathrm{T}\_i} \\ C_{\mathrm{CON}} = \sum_{i=1}^{N_{\mathrm{CON}}} C_{\mathrm{CON}\_i} = \sum_{i=1}^{N_{\mathrm{CON}}} L_{\mathrm{CON}\_i} P_{\mathrm{CON}\_i} \end{cases} \tag{2}$$

In the formulas: N_{T} and N_{CON} are the total number of distribution transformers and tie lines to be selected respectively; $C_{\mathrm{T\_i}}$ is the investment cost of the construction of the distribution transformer *i,* which is related to the type and capacity of the distribution transformer; $C_{\mathrm{CON\_i}}$ is the investment cost of the construction of the tie line i; L_{CON_i} is the length of the tie line i; P_{CON_i} is the investment cost of the construction of the unit length of the tie line i.

According to the Rural Power Network Planning and Design Guidelines, the capacity of distribution transformer should be selected according to the rural power development plan. Generally, it should be considered in five years. The specific calculation formula is as follows:

$$\begin{cases} S_{H} = R_{S} \times P_{H} \\ R_{S} = \dfrac{K_1 \times K_3}{\cos\varphi \times K_2} \end{cases} \tag{3}$$

In the formula: S_H is the required capacity of distribution transformer within the planned life (5 years); R_S is the capacity-load ratio; P_H is the current year's power load; K_1 is the load dispersion coefficient; K_2 is the economic load rate of distribution transformer; K_3 is the power load development factor; $\cos\varphi$ is the power factor.

Based on the upper distribution transformer planning and tie-line planning and the lower return low-voltage line planning, simulation is carried out to calculate the system maintenance cost and system loss cost. The specific formula is as follows:

$$C_{OPE} = C_M + C_L \tag{4}$$

In the formula: C_{OPE} is the cost of operation and maintenance, C_M is the cost of system maintenance, C_L is the cost of system loss.

The formulas for calculating the components of operation and maintenance costs are as follows:

$$\begin{cases} C_M = \sum_{i=1}^{N_T} C_{MT\_i} + \sum_{i=1}^{N_{LL}} C_{MLL\_i} + \sum_{i=1}^{N_{CON}} C_{MCON\_i} \\ C_L = C_{LT} + C_{LL} + C_{LCON} \end{cases} \tag{5}$$

In the formulas: C_{MT_i} is the maintenance cost of the distribution transformer i; C_{MLL_i} is the maintenance cost of the low-voltage line i; C_{MCON_i} is the maintenance cost of the tie-line i; C_{LT} is the loss cost of the distribution transformers; C_{LL} is the loss cost of the low-voltage lines; C_{LCON} is the loss cost of the tie-lines. The formulas for calculating the components of the system loss cost are as follows:

1） Loss cost C_{LT} of distribution transformers

$$\begin{cases} C_{LT} = \sum_{i=1}^{N_T} p_s W_{LT\_i} \\ W_{LT\_i} = \int_0^{T_{LT\_i}} P_{LT\_i}^t \mathrm{d}t \\ P_{LT\_i}^j = P_{0\_i} + \beta^2 P_{K\_i} \\ \beta = \left(\dfrac{S_i}{S_{Ni}} \right)^2 \end{cases} \tag{6}$$

In the formula: W_{LT_i} is the power loss of the distribution transformer i; p_s is the system price; P_{TLT_i} is the power loss of the distribution transformer i at the time t; P_{LT_i} is the no-load comprehensive power loss of the distribution transformer i; P_{K_i} is the rated comprehensive power loss of the distribution transformer i; β is the load factor of the distribution transformer; S_i is the apparent power output of the distribution transformer i; S_{Ni} is the rated capacity of the distribution transformer i.

2） Loss cost C_{LL} for low voltage lines

$$\begin{cases} C_{LL} = \sum_{i=1}^{N_{LL}} p_s \mathrm{W}_{LLL\_i} \\ \mathrm{W}_{LLL\_i} = \int_0^{\mathrm{T}_{LLL\_i}^j} P_{LLL\_i}^t \mathrm{d}t \\ P_{LLL\_i}^t = \left(I_{LLL\_i}^t\right)^2 R_{LL\_i} \end{cases} \tag{7}$$

In the formula: $W_{\mathrm{LLL\_i}}$ is the power loss of the low-voltage line i; p_s is the system price; $P_{\mathrm{LLL\_i}}$ is the active loss of the low-voltage line i at time t; $I_{\mathrm{LLL\_i}}$ is the current of the low-voltage line i at time t; and $R_{\mathrm{LL\_i}}$ is the resistance of the low-voltage line i.

3) Loss cost C_{LCON} of contact lines

$$\begin{cases} C_{\mathrm{LCON}} = \sum_{i=1}^{N_{\mathrm{CON}}} p_s \mathrm{W}_{\mathrm{LCON}\_i} \\ \mathrm{W}_{\mathrm{LCON}\_i} = \int_0^{\mathrm{T}^t_{\mathrm{LCON}\_i}} P^t_{\mathrm{LCON}\_i} \mathrm{d}t \\ P^t_{\mathrm{LCON}\_i} = \left(I^t_{\mathrm{LCON}\_i}\right)^2 R_{\mathrm{CON}\_i} \end{cases} \tag{8}$$

In the formula: $W_{\mathrm{LCON\_i}}$ is the power loss of the tie-line i; p_s is the system price; $P_{\mathrm{LCON\_i}}$ is the active power loss of the tie-line i at time t; $I_{\mathrm{LCON\_i}}$ is the current of the tie-line i at time t; and $R_{\mathrm{LCON\_i}}$ is the resistance of the tie-line i.

2.1.2. Generation method of distribution transformer power supply range based on Voronoi Diagram

Distribution transformer power supply range division usually adopts the principle of proximity. Because of the uneven distribution of load points, the load rate of distribution transformer varies greatly. In this paper, the weighted Voronoi diagram method is used to divide the power supply area of the planning area. The weights ω_i is introduced as the weights of the control point q_i. The power supply capacity of the distribution transformer, the control point of the reaction center, is optimized through several iterations to achieve the purpose of reasonable distribution of the power supply area.

2.2. Lower level model: low voltage line optimal planning based on Prim Algorithms

2.2.1. Lower voltage line planning model based on minimum construction cost

On the basis of the distribution and tie-line planning schemes generated by the upper model, the Prim algorithm is used to generate multiple low-voltage line planning schemes, so as to solve the optimal scheme with the lowest construction cost.

$$\min C_{\mathrm{LL}} = \sum_{i=1}^{N_{\mathrm{LL}}} C_{\mathrm{LL}\_i} = \sum_{i=1}^{N_{\mathrm{LL}}} l_{\mathrm{LL}\_i} p_{\mathrm{LL}\_i} \tag{9}$$

In the formula: C_{LL} is the construction cost of low-voltage lines; $C_{\mathrm{LL\_i}}$ is the construction investment cost of low-voltage line i; $l_{\mathrm{LL\_i}}$ is the length of low-voltage line i; and $P_{\mathrm{LL\_i}}$ is the unit length construction investment cost of low-voltage line i.

2.2.2. Optimal generation method of low voltage power supply line based on Prim Algorithms

The enumeration method is usually used to generate low-voltage distribution network, that is to say, all low-voltage distribution network planning schemes are enumerated and compared. Finally, the planning scheme with the lowest total investment cost is obtained, which is difficult to operate because of its large amount of calculation. Prim algorithm can search the minimum spanning tree in weighted connected graph. The tree composed of edge subsets searched by this algorithm includes not only all vertices in connected graph, but also the sum of weights of all edges is the smallest. In the process of low-voltage line planning, the distribution and load points are equivalent to the vertices of the connected graph, and the optional paths between the distribution and load points are equivalent to the edges of the connected graph, and the weights in the graph are equivalent to the investment of each edge. Finally, multiple groups of low-voltage line planning schemes are obtained by repeatedly generating the minimum spanning tree.

3. Case study

3.1. Summary of Examples and Parameters

To verify the effectiveness of the proposed planning method, an example is given to optimize the distribution transformer network planning for a typical class D power supply area on MATLAB R2014a platform. The simulation time is set to one year and the equivalent annual coefficient is set to 0.08.

3.2. The results of numerical examples

Through numerical simulation, the optimum scheme is obtained by optimizing the iteration of 76 generations. The number, capacity, address and operation scheme of new distribution transformers, the number and number of low-voltage lines and tie lines are shown in table1, the grid planning is shown in figure 1, the winter operation scheme is shown in figure 2, the spring, summer and autumn operation scheme is shown in figure 3.

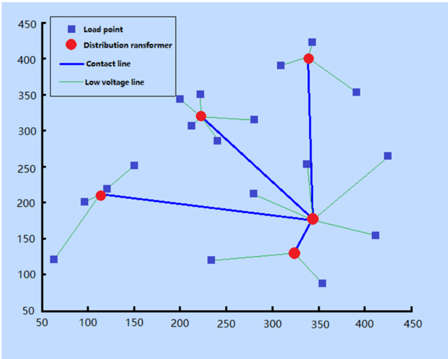

Figure 1. The optimal planning plan of a class D distribution transformer network

A total of 5 distribution transformers, 19 low-voltage lines and 4 tie lines are constructed. Because there are many electric heating loads in the D-type power supply area, the load in spring, summer and autumn is only 11.3% of that in winter. Therefore, a large-load operation scheme is adopted in winter, i.e. the low-voltage side tie-line switch of distribution transformer is disconnected. The specific operation efficiency and average loss are shown in table 1, and the grid structure is shown in figure 2.

Table 1. Parameters table of distribution transformer operation in winter.

Number	Capacity(kVA)	Load (kW)	operating efficiency（%）	Load loss(W)	Load loss(W)
1	315	162.32	69.68%	480	1243.82
2	400	228.45	77.23%	560	2119.36
3	200	108.21	73.16%	340	928.95
4	315	156.31	67.10%	480	1358.02
5	400	192.38	65.03%	560	1502.92

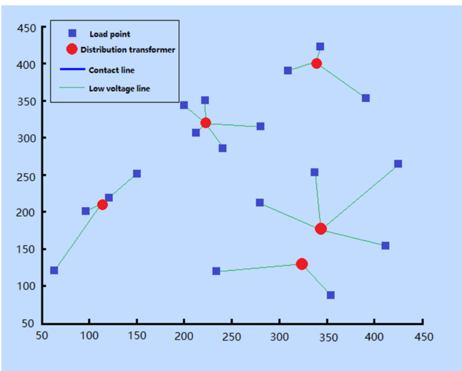

Figure 2. The winter operational diagram of a class D distribution transformer network.

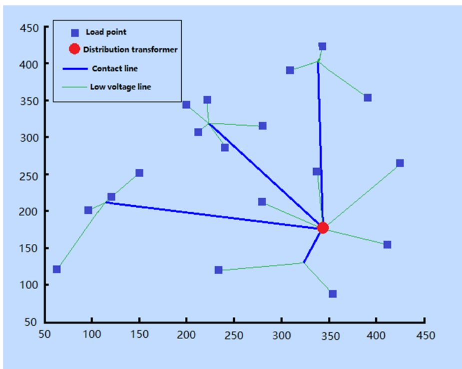

Figure 3. The spring, summer and autumn operational diagram of a class D distribution transformer network.

The type D power supply area adopts the small load operation scheme in spring, summer and autumn, i.e. closing the low-voltage side tie-line switch of the distribution transformer, and will not withdraw the distribution transformer in the small load operation scheme, i.e. No. 1, No. 2, No. 4 and No. 5. The specific operation efficiency and average loss are shown in table 2, and the specific network structure is shown in figure 3.

Table 2. Parameters table of distribution transformer operation in spring, summer and Autumn.

Number	Capacity(kVA)	Load (kW)	operating efficiency (%)	Load loss (W)	Load loss (W)
3	200	96.162	66.12%	340	758.554

Redundant distribution transformers can be withdrawn from operation in different seasons and different grid structures in small load season, which can optimize the grid structure, reduce no-load losses, improve the utilization rate of power grid equipment, and benefit the economic operation of distribution network. With the continuous development of rural economy, the peak-valley difference of power supply load in rural distribution network will continue to increase, and the advantages of power distribution transformer network optimization planning considering seasonal load will be more obvious.

4. Conclusion

Aiming at the region with a high proportion of seasonal load, this paper puts forward an optimal planning method of distribution transformer network adapting to seasonal load, establishes low-voltage tie-line between distribution transformers, changes the operation mode through the switch state of tie-line, and makes some distribution transformers withdraw from operation in low load season. In this method, a bi-level programming model of distribution transformer network is constructed with the objective of minimizing the comprehensive cost, and solved by combining genetic algorithm, Voronoi and Prim algorithm. The results show that this method provides a new idea for the development of power grids in coal-to-electricity conversion areas, is conducive to reducing no-load losses, and achieves the dual purpose of improving power supply reliability and economy, and has important significance for promoting enterprises and maintaining sustainable development.

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