Method for selecting location and capacity of ring station in the urban distribution network

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Abstract. Aiming at the lack of a systematic research method on the distribution of ring station in the existing 10kV urban medium voltage distribution network research, a method of ensuring the location and capacity of ring station based on the weighted Voronoi diagram is proposed. First, analyze the location and capacity of ring station based on the structure of the urban medium-voltage distribution network; Second, in view of the location and capacity of the ring station of the urban medium voltage distribution network, the line investment of the upper-level to the ring station, the investment cost of the ring station, and the line investment of the lower-level to the ring station are comprehensively considered, and build the mathematical model. Third, a method of ensuring the location selection and capacity determination of ring station based on weighted Voronoi diagrams and a solution process are proposed. Finally, an example is used to verify the effectiveness and practicability of the proposed method.

Keywords: urban medium-voltage distribution network; ring station; the weighted Voronoi diagram.

1. Introduction
The distribution network is important in the power system. Scientific distribution network planning can effectively reduce the losses of the system network [1] and the power outage. It can greatly improve the efficiency of the power grid operations. For a long time, the structure of the medium-voltage distribution network has been complicated and uneven, mainly due to the unbalanced regional load development and the lack of uniformity in the medium-voltage distribution network, and the overall planning [2].

The urban medium-voltage power distribution network uses substations as the upper-level power source [3], and the ring station is used as the core node to connect between the substations, and the ring station is used as the power source for lower-level users.

The ring station plays the role of substation bus extension and changing the voltage level. It is the connection bridge between the upper-level substation and the lower-level users. The location and capacity of the ring station will affect the investment cost of the upper and lower lines. So, it is very important to select the location and capacity of the ring station.

Literature [4] puts forward the basic principle of the hierarchical division of the medium voltage distribution network, divides the distribution network structure into several levels, and expounds the application of the ring station, but for the selection of the ring station capacity, only according to
empirical value. There are no quantitative methods for determining the capacity of the ring station; Literature [5] conducted the hierarchical structure of the 10kV medium voltage distribution network, gave the capacity configuration scale of the ring station, and gave the method of determining the position between the ring station and the substation. However, only the theoretical interval of the distance between the ring station and the substation is given, and the location of the ring station is not accurately determined. Literature [6] determined the optimal number and optimal location of the ring station, but only considered the investment cost of the ring station and the investment cost of line from the ring station to the lower-level, and it did not consider the investment cost of the line from the ring station to the upper-level.

In summary, the existing research on the location of ring station does not comprehensively consider the interaction between substation, ring station of the medium voltage distribution network, and lower-level load. So this paper firstly analyze the location and capacity of ring station based on the structure of the urban medium-voltage distribution network; Second, in view of the location and capacity of the ring station of the urban medium voltage distribution network, the line investment of the upper-level to the ring station, the investment cost of the ring station, and the line investment of the lower-level to the ring station are comprehensively considered, and build the mathematical model. Third, a method of ensuring the location selection and capacity determination of ring station based on weighted Voronoi diagrams and a solution process are proposed. Finally, an example is used to verify the effectiveness and practicability of the proposed method.

2. The Influencing factors of location and capacity of ring station
In the study of the location and capacity of the ring station of the urban medium-voltage distribution network, it is necessary to comprehensively consider the line investment of the upper-level to the ring station, the investment cost of the ring station, and the line investment of the lower-level to the ring station. On this basis, determine the number of ring stations, the capacity of the ring station and the location of the ring station.

Therefore, it is necessary to clarify the possible impacts when the number, capacity, and location of ring stations are different.

(1) The impact on the investment of ring station
The number of ring stations affects the investment cost of ring stations. When there are more ring stations, the investment cost of the ring stations is greater; when there are fewer ring stations, the investment cost of the ring stations is smaller.

(2) The impact on the investment of the line investment of the upper-level to the ring station
The urban medium voltage distribution network is based on the ring station. Therefore, when the location of the ring station is different, it will affect the length of the line between the upper-level to the ring station, and then affect the investment of the line investment of the upper-level to the ring station.

(3) The impact on the investment of the line investment of the lower-level to the ring station
When the capacity of the ring station is large, and the power supply range of each ring station is larger, the length of the line of the lower-level to the ring station will increase, and the corresponding outgoing line investment cost will increase; When the capacity of the ring station is small, and the power supply range of each ring station is smaller, the length of the line of the lower-level to the ring station will decrease, and the corresponding outgoing line investment cost will decrease.

3. Mathematical model of ring station of the urban medium-voltage distribution network
In the planning of the ring station in the urban medium-voltage distribution network, the impact of the line investment of the upper-level to the ring station, the investment cost of the ring station, and the line investment of the lower-level to the ring station should be comprehensively considered. To meet the optimal condition of the total economic cost, the location and capacity of the ring station should be selected, so the optimization object is the location and capacity of the ring station.
3.1. **Objective function**

The objective function of location and capacity of ring station includes three parts: the line investment of the upper-level to the ring station, the investment cost of the ring station, and the line investment of the lower-level to the ring station, which is shown in formula (1).

\[
F = Z_1 + Z_2 + Z_3
\]  \hspace{1cm} (1)

\(Z_1\) represents the investment cost of the ring station, \(Z_2\) represents the line investment of the upper-level to the ring station, \(Z_3\) represents the line investment of the lower-level to the ring station. The specific expressions of \(Z_1\), \(Z_2\), and \(Z_3\) are shown in formula (2), formula (3), and formula (4) which uses the equivalent expression.

\[
Z_1 = \alpha \left[ \frac{r_0 (1 + r_0)^m}{(1 + r_0)^m - 1} \right] \times N_k \hspace{1cm} (2)
\]

\[
Z_2 = \beta \left[ \frac{r_0 (1 + r_0)^n}{(1 + r_0)^n - 1} \right] \times \sum_{k=1}^{N} L_k \hspace{1cm} (3)
\]

\[
Z_3 = \gamma \left[ \frac{r_0 (1 + r_0)^n}{(1 + r_0)^n - 1} \right] \times \sum_{k=1}^{N} L_n \hspace{1cm} (4)
\]

\(\alpha\) represents the construction cost of the ring station, \(r_0\) represents the discount rate, \(m\) represents the service life of the ring station; \(\beta\) represents the investment cost of the ring station line supplied by the unit substation, \(n\) represents the depreciation years of the line, and \(L_k\) represents the length of the \(k\)-th upper-level line of the ring station, \(N\) represents the total number of lines in the ring station;

\(\gamma\) represents the investment cost of the line which is from the ring station to the lower-level subscriber, \(N_k\) represents the number of ring station, and \(L_n\) represents the sum of the length of the line which is from the ring station to the lower-level within the power supply range of each ring station.

3.2. **Boundary condition and constraint**

(1) **Boundary condition**

This paper limits the scope of the study to a area between the two substations, and the load density of the area is known.

The equipment investment cost in the ring station, the cost of the ring station, the investment cost of the line from the substation to the ring station, and the investment cost of the line from the ring station to the lower-level are also the boundary conditions of this study.

(2) **The constraint**

1) **Constraint on the capacity of ring station**

According to the capacity of the substation and the transmission capacity of the line, the maximum capacity of the ring station can be determined. This constraint indicates that the capacity of the ring station cannot exceed the maximum value.

2) **The load matching constraint**

\[
R_i T_i = R_{iq} T_{iq} \hspace{1cm} (5)
\]

\(R_i\) and \(T_i\) respectively represent the capacity and load factor of the \(i\)-th feeder of the ring station; \(R_{iq}\) and \(T_{iq}\) represent the capacity and load factor of the distribution transformer connected to the \(i\)-th feeder of the ring station.
3) The voltage constraint

The constraint condition represents the voltage operation constraint of each feeder terminal node of the distribution network, as shown in formula (6)

\[
V_{iq\min} \leq V_{iq} \leq V_{iq\max}
\]

(6)

In the above formula, \(V_{iq}\) represents the end node voltage of the \(q\)-th feeder from the \(i\)-th ring station, and \(V_{iq\max}\) and \(V_{iq\min}\) are the upper and lower limits of the corresponding feeder end node voltage.

4. Location and capacity method of ring station based on the weighted Voronoi diagram

(1) Properties of the weighted Voronoi diagram

The weighted Voronoi diagram is suitable for the spatial division when the weights of each occurrence element are significantly different. The weighted Voronoi diagram is defined as follows:

\[
P \text{ is a set of control points in the space, then the formula (7) is as follows:}
V(p_i, \lambda_i) = \{x \in V(p_i, \lambda_i) | \frac{d(x, p_i)}{\lambda_i} \leq \frac{d(x, p_j)}{\lambda_j}\}
\]

(7)

\(D(p_i, p_j)\) represents the distance between the \(p_i\) and the \(p_j\), \(p_i \neq p_j\), \(i \neq j\), \(x\) is any point in the place.

The place is divided into \(n\) parts, and the division of the plane determined by \(V_n\) is called a point-weighted Voronoi diagram, and \(\lambda\) is called the weight of \(p_i\).

(2) Location and capacity method of ring station based on the weighted Voronoi diagram

Consider \(n\) ring stations as \(n\) control points in the place. In order to reflect the power supply capacity of the ring station, the square root of the load of the ring station power supply area and the ratio of the ring station capacity are used as the weight of the control point. During the process of dividing the power supply range of the ring station, the weight is adjusted by multiple iterations, and the planning area is divided into \(n\) polygonal power supply areas, and \(n\) polygonal power supply areas are the power supply ranges of \(n\) ring station.

In summary, the specific steps of ring station planning based on the specific Voronoi diagram are as follows:

① Determine the initial site address of the ring station according to the principle of geometric equalization.

② The initial weight is 1, and the Voronoi diagram is constructed with the initial site address of the ring station as the vertex. The Voronoi diagram can generate a V curve corresponding to each ring station, and the V curve is the power supply range of each ring station.

③ Calculate the power supply capacity of each ring station

④ Judge whether the capacity of the ring station meets the constraint conditions, if it is satisfied, proceed to step ⑤, otherwise adjust the weight of the ring station and return to step ②. The weight generation takes into account the upper limit of the capacity of each ring station, the total load carried by each ring station in the previous partition and the partition load density. By adjusting the boundary of the ring station that does not meet the standard, so that the capacity of each ring station tends to be reasonable.

⑤ Use the minimum objective function as the criterion to optimize the site of the ring station.

⑥ If the sum of distance change of the ring station is less than the threshold, the iteration ends; otherwise, return to step ①.

The specific ring station planning flowchart is shown in Fig.1
The Voronoi diagram is constructed with the ring station as the node, and the power supply range of the ring network unit is obtained.

- Get the capacity of the ring station
- Optimize the site based on the principle of minimum function, and judge if the change is less than threshold
- Adjust the weight of ring station

**Fig. 1** Flowchart of site selection and capacity determination of ring station

5. Case Analysis

The scope of this research is within a group of power supply unit, there are 392 lower-level loads. The size of each load is 35.7kW, and the load density is 30000kW/km², as shown in Fig.2.

![Figure 2: The diagram of the connection area between two substations](image)

According to the total value of the load in the contact area formed between the two substations and the capacity range of the ring station, it can be determined that the number of ring station that may be included in the group of the area is 3–6. Table 1 shows the best capacity of each ring station when there are 3 to 6 ring stations in the contact areas between the two substations.
Table 1. The capacity results of the ring station

| The number of the ring stations | The capacity of the ring stations (kW) |
|-------------------------------|---------------------------------------|
| 3                             | 3831, 6338, 3831                      |
| 4                             | 2792, 4208, 4208, 2792                |
| 5                             | 2114, 2888, 3996, 2888, 2114          |
| 6                             | 1470, 2360, 3170, 3170, 2360, 1470    |

Table 2 shows the investment of the ring stations, the line investment of the upper-level power supply to the ring station, and the line investment of the lower-level power supply to the ring station when the connection area between the two substations includes 3~6 ring stations.

Table 2. Each investment results of the ring station

| The number of the ring stations | The line investment of the upper-level to the ring station | The line investment of the lower-level to the ring station | The investment of the ring stations | The total investment |
|--------------------------------|----------------------------------------------------------|----------------------------------------------------------|-----------------------------------|---------------------|
| 3                              | 937                                                      | 1711                                                    | 210                               | 3018                |
| 4                              | 872                                                      | 1442                                                    | 280                               | 2729                |
| 5                              | 1055                                                     | 1276                                                    | 350                               | 2799.75             |
| 6                              | 1020                                                     | 1142                                                    | 420                               | 2688.25             |

Figure 3 shows the location and capacity results of ring station when the number of ring station is 4.

Fig. 3 The graph when the number of ring station is 4

It can be obtained from the above results that the location and capacity of each ring station can be obtained under the best economic cost by using the Voronoi algorithm to select the location and capacity of each ring station.

6. Conclusion
First, analyze the location and capacity of ring station based on the structure of the urban medium-voltage distribution network; Second, in view of the location and capacity of the ring station of the urban medium voltage distribution network, the line investment of the upper-level to the ring station, the investment cost of the ring station, and the line investment of the lower-level to the ring station are comprehensively considered, and build the mathematical model. Third, a method of ensuring the location selection and capacity determination of ring station based on weighted Voronoi diagrams and a solution process are proposed. Finally, an example is used to verify the effectiveness and practicability of the proposed method. It provides theoretical guidance for the construction and lean management of urban medium voltage distribution network.

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