The shunt capacitor placement based on partition method in middle level distribution networks

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Abstract. The capacitor placement based on rational reactive power partition can reduce the power loss and increase benefits in middle distribution systems. So this paper proposes a new capacitor placement method based on reactive power partition. First the distribution is partitioned by Depth First Search algorithm and the principle that the reactive power of each partition load is the most similar. Then the number of node is also more similar in each partition. This is helpful for the selection of locations. Secondly the locations and capacity are simultaneously optimized after partition and obtain more benefits. Finally the 94 node distribution system proves the advantage and practicality of the proposed algorithm.

1. Introduction

The medium voltage distribution network shunt capacitor configuration [1] is to determine the number of compensation points, the position and the number of groups on the 10kV feeder line, which can effectively improve the voltage distribution, reduce the network loss, release the transmission capacity of the feeder, and improve the economic benefits. The study of this problem, if combined with the following two characteristics, will obtain better compensation effects: 1) the radial structure of the distribution network; 2) the reactive power cannot be transmitted on a large scale or over a long distance.

The medium voltage distribution network shunt capacitor configuration has been widely studied due to its simplicity and easy implementation [2-8], but this method does not make full use of the radiation structure characteristics of the distribution network. And the compensation point is re-optimized. The single-sequence optimization method of compensation capacity has problems such as over-compensation and easy to fall into the local optimal solution, and the actual compensation effect is not good.

Literature [9-14] studied the configuration of shunt capacitors based on the radiation structure characteristics of the distribution network, and optimized the compensation capacity and position, but...
reduced the tree-shaped distribution network into a dressing net, which reduced the calculation accuracy.

In [15], based on the characteristics that reactive power can not be transmitted on a large scale and over long distance, the reactive power partition method based on reactive quadratic precision moment is proposed to study the configuration of shunt capacitors in medium voltage distribution network, which simplifies the difficulty of the problem and obtains the better compensation effect. However, the reactive secondary precision moment of each node is calculated by using the root node as the only reactive power point, and does not consider the situation of multiple reactive power points after compensation. This is easy to cause the reactive power partition at the end of the feeder to be compensated for small reactive load, which tends to result in a small number of nodes to be compensated. The reactive power load to be compensated in the reactive power partition near the root node is large, which tends to result in a large number of nodes to be compensated. The final consequence is that when the compensation point is determined by the reactive partition, the number of compensation nodes that can be selected at the end of the feeder is less, the range of the selection is reduced, and the compensation effect is affected, especially for long-distance feeders.

For this reason, this paper uses the conditions of the reactive power load to be compensated for equal reactive power and the depth-first search algorithm to divide the reactive partition, so that the number of points to be compensated in each partition is the closest, and try to avoid the reactive power to be compensated at the end of the feeder. The problem of a small number of expansions expands the selection range of compensation points for each reactive partition. At the same time, the cutting optimization method is used to study the compensation point position and capacity while optimizing, which improves the calculation efficiency.

2. Definition and division of reactive partitions

2.1 Definition

The radial medium voltage distribution network can be regarded as the tree $T$. If the branch $b_i$, $i = 1, 2...n$ ($n$ is the number of branches), meeting the following conditions:

1) Branch $b_i$ is connected graph;

2) The intersection of branches is empty;

3) The union set of each branch is $T$;

So the branch $b_i$ is a reactive partition.
As shown in the radial distribution network shown in figure 1, the branches $b_1, b_2, b_3$ are all connected graphs without a common side, together forming a radial distribution network, and they are three reactive partitions of the distribution network. Since the branch is used as the reactive partition, the continuity of the node and the branch topology in the reactive partition is guaranteed.

### 2.2 Division of reactive partitions

The root node can only compensate downstream, and the parallel capacitor can be compensated separately to the upstream and downstream. The reactive load in the reactive partition of the root node is approximately half of the remaining reactive partition, and the rest of the reactive power zones to compensate the reactive load as close as possible. The approximate calculation formula for the reactive power load value to be compensated for each reactive partition is given below:

$$
Q_{PT} = 2Q_\Sigma / (2N + 1)
$$

Where, $Q_\Sigma$ is the total reactive load to be compensated; $N$ is a given number of compensated points.

Based on equation (1) and depth-first search algorithm, the flowchart of partition is given:

Since the branch closest to $QQ$ is divided as the reactive power partition each time, the number of compensating points in each reactive power partition can be close to the largest extent, avoiding the phenomenon of the small number of compensating points in the reactive power partition at the feeder end in literature [15] and ensuring the topological continuity in the reactive power partition.
3. Reactive power optimization planning based on cut optimal distribution network

3.1 Mathematical model of reactive power optimization programming

Establish the objective function with the maximum annual economic benefit:

\[
\begin{align*}
\text{Max } F &= (\Delta P_C^{\text{max}} \times t_{\text{max}} + \Delta P_C^{\text{normal}} \times t_{\text{normal}} + \Delta P_C^{\text{min}} \times t_{\text{min}}) \times K_D \\
&\quad - \sum_{j=1}^{N} (Q_{c_j} \times C_{c_j} \times K_{c_j}) \times \left(\frac{\gamma \times (1+\gamma)^a}{(1+\gamma)^a - 1}\right) \\
&\quad - N_c \times C_{c} \times K_{c}
\end{align*}
\]

(2)

The first item on the right side of the equation (2) is the annual income caused by the loss after compensation. The second item is the current value of the investment cost of the compensation equipment, which is equivalent to the annual value. The third item is the annual operating cost of the capacitor; \(\Delta P_C^{\text{max}}, \Delta P_C^{\text{normal}}, \Delta P_C^{\text{min}}\) respectively its’ the loss saved under the maximum, general and minimum load conditions; \(t_{\text{max}}, t_{\text{normal}}, t_{\text{min}}\) are the annual running time under the maximum, normal and minimum load conditions respectively; \(K_D\) is the electricity price; \(N_c\) is the compensation capacitor group.
number; \( Q_{cj} \) is the capacitor single group capacity; \( C_{cj} \) is the compensation capacitor single-unit capacity cost; \( K_{cj} \) is the compensation group number; \( \gamma \) is the discount rate; \( \tau \) is the capacitor operation period; \( C_{op} \) is the single-group capacitor operation cost.

In addition, the constraint equations for the power flow equation, the node voltage, and the branch current limit must be met.

3.2 Quick Determination of Compensation Point Position in Reactive Partition

As in the literature [15], each reactive partition can only set at most one compensation point, but the intermediate reactive partition, that is the end node of the reactive partition is also the root node of other reactive partitions, the first of the reactive partitions. The node is the root node of the distribution network. The reactive partition \( b_i \) shown in figure 1 is the intermediate reactive partition. The reactive load of the intermediate reactive partition can be compensated by the compensation point of the downstream reactive partition and the root node of the distribution network. This paper stipulates that the intermediate reactive partition does not set the compensation point. The results of the later example verify that the intermediate reactive partition does not set the compensation point than the set compensation point helps to improve the economic benefit of compensation.

The optimization process of the compensation point position in the reactive partition is as follows: Assume that the root node of the reactive partition is the power point, calculate the annual economic benefit of each node as the point to be compensated, and take the node with the maximum value of (2) as the reactive partition compensation. The advantage is that it can quickly determine the compensation point position of each reactive partition without complicated optimization calculation.

3.3 Reactive power optimization planning algorithm based on cutting optimal distribution network

Reactive power partition in the section 2.2, the assumption is that the root node is the source, and the actual distribution network only a root node is the source, the reactive power partition root node is not the source, according to the calculation of section 2.2 of reactive power compensation point of partition location is not the final result, the compensation point position toward the direction of distribution network root node, in order to obtain better compensation effect.

In all compensation points, if only the \( i \)th compensation point is moved upstream in its reactive power partition by one position, and the rest of the compensation points remain unchanged, the value of equation (2) and the compensation capacity of each compensation point are calculated by using the range of action method in reference [16] to complete a one-time optimization calculation, and the value of equation (2) is considered as a cut. If \( i = 1, \ldots, n_c \), \( n_c \) is the number of compensation points, and the above process is repeated, one cut is formed each time, and all cuts constitute a cut set. It needs to be explained that, for each calculation of a cut, the compensation points of the movement during the last calculation of a cut should be returned to the original position.

The optimal reactive power planning method based on cut optimization is as follows:
1) Based on the positions of compensation points determined in section 2.2, all cuts are calculated to form cut set and the maximum cut is selected.

2) If the maximum cut is greater than 0, the compensation point corresponding to the maximum cut is actually moved upstream by one position; Otherwise turn to step 4;

3) Based on the position of the compensation point determined in step 2, calculate all the cuts, and select the maximum cut, and turn to step 2);

4) Output the existing position, compensation capacity, line loss rate and economic benefit of each compensation point.

In the above algorithm, the rounding method rounds the number of compensation groups. The cutting optimization method quickly realizes the simultaneous optimization of the compensation point position and capacity, and has high computational efficiency and global search capability.

4. Case studies

As shown in Figure 3, a 94-node medium voltage distribution network in a city, the root node voltage is 10kV, the planning period is 10 years, the electricity price is 0.6 ¥/kWh, the discount rate is 0.1, the capacitor single group capacity is 30kvar, the price is 10,000 ¥/group, the number of compensation points given is 2, and the parameters are shown in the attached table.

In the above algorithm, the rounding method rounds the number of compensation groups. The cutting optimization method quickly realizes the simultaneous optimization of the compensation point position and capacity, and has high computational efficiency and global search capability.

4.1 The partition results

The total reactive load to be compensated in this distribution system is 1774.6kvar. The approximate value of reactive load to be compensated in each reactive power partition is 709.84kvar according to equation (1). Table 1's reactive power partition is obtained by combining the algorithm in figure 2.

| Method         | Partition 1 | Partition 2 | Partition 3 |
|----------------|-------------|-------------|-------------|
| Proposed method| 60-94       | 9-44        | 1-9,9-59    |
| In[15]         | 70-94       | 28-44       | 45-69,1-28  |

Figure 3. The 94 nodes distribution system.
It can be seen from table 1 that the reactive power partitions 1 and 2 contain more nodes than the literature [15], which proves that for long-distance feeders, the literature [15] may cause fewer reactive nodes in the feeder end, reducing the number of nodes. The number of points to be compensated in the work partition can affect the optimization result, and the nodes 70-72 and the nodes 73-94 in the reactive partition 1 are not continuous in topology.

4.2 Reactive power optimization planning results of distribution network

Table 2 gives the results of the parallel capacitor configuration based on the reactive partition of table 1 in the method and literature [15]. The literature [15] contains fewer nodes due to the reactive partition, resulting in less choice of compensation points and compensation economic effects. Compared with the results of the method in this paper, although the improved particle swarm optimization algorithm in [15] can search for the optimal solution in a large range, the computational efficiency is low.

| Method                        | Position of point | Group number | Line Loss Rate (%) | Annual economic benefit (ten thousand yuan) | Time (s) |
|-------------------------------|-------------------|--------------|--------------------|-------------------------------------------|----------|
| This paper with 2 compensation points | 60/24             | 20/20        | 6.24               | 8.57                                      | 2.7      |
| The literature [15] with 2 compensation points | 73/28             | 20/20        | 6.31               | 8.36                                      | 303      |
| The literature [15] with 3 compensation points | 83/32/45          | 15/12/13     | 5.76               | 7.95                                      | 317      |

In section 2.2 of this paper, no compensation points are set for the intermediate reactive partition. The literature [15] sets a compensation point for each reactive partition. The third row of table 3 gives the compensation points for each reactive partition. The optimization result adding a compensation point, reduces the line loss rate, but due to the increase of investment, the annual economic benefit is also reduced, indicating the superiority of the intermediate reactive partition without setting the compensation point.

In order to verify the global search ability of the optimal reactive power optimization planning method, the improved particle swarm optimization algorithm in [15] is used. Based on the reactive partitioning result of this paper, the optimization result is the same as the first row in table 2; The reactive power partitioning of the third row of table 2 uses the cutting optimization method to determine the position and capacity of the compensation point, and obtains the same optimization result as the third row of table 2. The calculation example shows that the search ability of the best method is the same as that of the improved particle swarm optimization algorithm. It has strong global search ability, but the cut optimal method is calculated in seconds, and the efficiency is much higher than the improved particle algorithm.
5. Conclusion

Based on the depth-first search algorithm and the partitioning that divides the reactive load of each partition to the maximum extent, the number of compensation points in the reactive partition at the end of the feeder is expanded, which lays a foundation for better reactive power optimization planning. The application of the cutting optimal method realizes the simultaneous optimization of the compensation point position and capacity, which helps to improve the economic benefit and calculation efficiency of compensation. The actual system example results verify that the proposed method improves economic efficiency and computational efficiency compared to existing methods.

Finally, the algorithm is simple and easy to implement, and has great practical application value.

### Schedule: System Parameter

| Starting node | End node | Impedance (kw, kvar) | Maximum load (kw, kvar) | General load (kw, kvar) | Minimum load (kw, kvar) |
|---------------|----------|----------------------|------------------------|------------------------|------------------------|
| 1             | 2        | 0.021, 0.030         | 0, 0                   | 0, 0                   | 0, 0                   |
| 2             | 3        | 0.072, 0.047         | 59.6, 1.9              | 35.6, 1.1              | 17.8, 0.57             |
| 2             | 4        | 0.225, 0.33          | 0, 0                   | 0, 0                   | 0, 0                   |
| 4             | 5        | 0.280, 0.36          | 118.9, 8.3             | 71.3, 8.5              | 35.6, 8.9              |
| 5             | 6        | 0.09, 0.1125         | 118.9, 8.8             | 71.3, 8.5              | 35.6, 8.9              |
| 4             | 7        | 0.072, 0.09          | 0, 0                   | 0, 0                   | 0, 0                   |
| 7             | 8        | 0.02, 0.197          | 59.6, 1.3              | 35.6, 1.2              | 17.8, 0.5              |
| 7             | 9        | 0.06, 0.045          | 0, 0                   | 0, 0                   | 0, 0                   |
| 9             | 10       | 0.35, 0.322          | 0, 0                   | 0, 0                   | 0, 0                   |
| 10            | 11       | 0.156, 0.08          | 118.9, 8.8             | 71.3, 8.5              | 35.6, 8.9              |
| 10            | 12       | 0.03, 0.046          | 0, 0                   | 0, 0                   | 0, 0                   |
| 12            | 13       | 0.446, 0.291         | 118.9, 8.3             | 71.3, 8.2              | 35.6, 8.9              |
| 12            | 14       | 0.325, 0.299         | 0, 0                   | 0, 0                   | 0, 0                   |
| 14            | 15       | 0.257, 0.155         | 0, 0                   | 0, 0                   | 0, 0                   |
| 15            | 16       | 0.216, 0.141         | 118.9, 8.8             | 71.3, 8.5              | 35.6, 8.9              |
| 15            | 17       | 0.216, 0.141         | 118.9, 8.3             | 71.3, 8.2              | 35.6, 8.9              |
| 18            | 19       | 0.108, 0.07          | 118.9, 8.8             | 71.3, 8.5              | 35.6, 8.9              |
| 18            | 20       | 0.175, 0.161         | 0, 0                   | 0, 0                   | 0, 0                   |
| 20            | 21       | 0.452, 0.282         | 59.4, 3.9              | 35.6, 2.9              | 17.8, 0.5              |
| 21            | 22       | 0.325, 0.299         | 118.9, 8.8             | 71.3, 8.5              | 35.6, 8.9              |
| 22            | 23       | 0.252, 0.164         | 118.9, 8.3             | 71.3, 8.2              | 35.6, 8.9              |
| 23            | 24       | 0.125, 0.115         | 0, 0                   | 0, 0                   | 0, 0                   |
| 24            | 25       | 0.36, 0.15          | 59.4, 3.9              | 35.6, 2.9              | 17.8, 0.5              |
| 25            | 26       | 0.125, 0.115         | 0, 0                   | 0, 0                   | 0, 0                   |
| 26            | 27       | 0.250, 0.150         | 118.9, 8.3             | 71.3, 8.2              | 35.6, 8.9              |
| 27            | 28       | 0.45, 0.414          | 0, 0                   | 0, 0                   | 0, 0                   |
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