Mesh Planning Optimization for Urban Distribution Network with High Reliability

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Abstract. Modern distribution network has a huge volume and a wide range of points, so the difficulty of construction and transformation of distribution network often lies not in technological innovation, but in the operability of planning scheme, adaptability and flexibility of network structure. Therefore, an optimization model of mesh planning for high reliability power supply in urban power grid is proposed. Firstly, the planning process is optimized to avoid the cyclic adjustment of power supply mesh and power supply unit division. Secondly, a target network architecture and power supply unit partition model for medium-voltage power grid are proposed, which can meet the double power demand of important power users and ensure no cross-supply between units. Finally, an example of mesh planning in a city center in Hubei Province of China is given, and the application of the optimization method is described in detail. The results show that the method is easy to carry out, and effectively improves the reliability of power supply in urban power grid.

1. Introduction

In March 2019, the Chinese State Energy Administration's Power Reliability Management and Engineering Quality Supervision Center issued the National Report on Power Supply Reliability Indicators for Ultra-large Cities. The report shows that in 2018, the reliability indices for power supply in 14 Ultra-large Cities in China continued to improve, with the power supply reliability rate reaching more than 99.95%. The focus of modern distribution network planning has changed from simply satisfying the demand of load growth to satisfying users' high-quality demand for electricity in China.

Because the medium-voltage distribution network is generally formed by the natural extension of load distribution, the current urban distribution network presents a messy complex form. There are many problems, such as unreasonable power supply zoning, circuitous power supply lines, complex line connections, which are not conducive to the improvement of power supply reliability and are harmful to the power user's experience.

At present, a lot of achievements have been made in mesh planning [1-6] and connection mode research of medium-voltage network [7-14]. However, there are still no effective solutions to the following problems: 1) Developing a highly operable partition method for power supply mesh and power supply unit. 2) Research on the target network structure and wiring mode to meet the demand of urban power consumption and to adapt to the future development of power grid. 3) Research on the distribution network planning scheme which is conducive to simplifying the maintenance of
equipment and dispatching operation. Because of the close relationship between distribution network planning and power industry, it is necessary to formulate a feasible, economical and practical mesh planning scheme. Therefore, based on the existing mesh planning research, this paper proposes a mesh planning optimization model, the contributions are as below: 1) The process of mesh planning is optimized to avoid the cyclic adjustment of mesh and unit division. 2) A target network structure and power supply unit division model for medium-voltage power grid is proposed, which can meet the double power demand of important power users and ensure that there is no cross-supply between power supply units. 3) The recommended network structure is concise, and is conducive to maintenance and dispatch.

2. Mesh planning model for high reliability power supply demand area
The main content and process of the optimization process is similar to the existing mesh planning [1-5] of distribution network. It mainly includes data collection, power supply mesh and power supply unit division, power grid status analysis, load forecasting, target grid planning and transitional scheme determination, distribution automation planning, etc. The optimization method in this paper is mainly optimized in two aspects. Firstly, in the planning process, the division of power supply mesh and power supply unit is taken as two steps successively. After obtaining the current information, the division of power supply mesh is carried out, while the division of power supply unit is based on load forecasting and target grid planning to avoid the cyclic adjustment of mesh and unit division. Secondly, a more detailed model is proposed for the construction of target network and the division of power supply units in medium-voltage power network, which is suitable for industrial parks with more important power users [15] and urban power grid areas with higher power supply reliability requirements.

2.1. Optimized mesh planning process
The optimized mesh planning process is as follows:
(1) Data collection. There are three categories of data: first, government economic and social development planning, urban master planning, regulatory detailed planning, power facilities layout planning, etc. Second, equipment account data of medium-voltage distribution transformers and lines from PMS2.0 system and GIS platform, and operation data of substation, distribution transformers and lines from SCADA system. The third is the data of distribution transformer, line power and user's report from the electric power information collection system.

(2) Divide power supply mesh. The collected basic data is used to divide the power supply mesh. There are two basic principles. First, the mesh division is bounded by obvious geographical forms such as roads, rivers and hills, and corresponds to the functional zoning in urban regulatory detailed planning. Second, it is necessary to consider the distribution of 220kV, 110kV and 35kV substations, regional load and electricity consumption. The power mesh should be moderate in scale and relatively independent in power supply scope. In long-term planning, it should generally include 2-4 public substations with 10kV trunk lines, and one substation can be divided into 2 or 3 power supply meshes. Once the mesh is determined, it is generally inappropriate to change it.

(3) Current situation analysis of power grid. In every power supply mesh, analyses the current situation of power grid layout and load distribution, and lists the existing problems in network structure, operation status, distribution automation and corridor.

(4) Load forecasting. The long-term load forecasting is carried out first, and then the short-term and medium-term load forecasting is carried out. Long-term load forecasting is based on spatial load forecasting method. Natural growth method and large consumers method is used in short- and medium-term load forecasting.

(5) Target network structure planning and power supply unit division in every mesh. On the basis of long-term load forecasting, the target network structure planning of 10kV trunk lines is carried out in every mesh. And then divide the mesh into several power supply units. In order to meet the double power demand of important power users and ensure that there is no cross-supply between power
supply units, there are three types for the composition of power supply units in urban distribution network: two pairs of overhead single-tie lines, two cable single-loop networks and one cable double-loop network. The advantages of these three wiring modes will be explained in detail in the next section. The division of power supply units can be revised on a rolling basis according to the municipal planning.

(6) Make the transition plan of every power supply unit. Based on the target network structure and load forecasting results in the short and medium term, the transition process of power supply unit is determined, and a 10kV main grid transition scheme is proposed.

(7) Distribution automation planning and corridor planning. Distribution automation planning is carried out synchronously in combination with primary target network, and corridor planning is carried out according to the requirements of main distribution network and urban road planning, as well as the construction requirements of secondary communication network.

(8) Specify the annual transitional plans and clarify the annual construction plans and construction schedule.

Compared with the existing mesh planning process [1-2], the optimized process avoids the problem of cycle adjustment of meshes and units’ division. This is because, in the optimized process, the mesh division is prior to unit division, and only based on the geographical form and the distribution of higher-voltage substations, which has nothing to do with the structure of 10kV power grid. In the existing process, the modification of 10kV target structure can lead to the re-division of power supply meshes and units. A comparison of the two mesh planning processes is shown in Figure 1.

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**Figure. 1** The ordinary mesh planning process (left) and the optimized mesh planning process (right)

2.2. Target network structure and power supply unit division model
In urban distribution network, the recommended typical wiring modes are overhead single-tie line, cable single-loop network and cable double-loop network, the reason is as follows:

(1) As the load increasing, with the simple structure of a single connection, it can easily modify
the location of common open contact nodes and adjust the load distribution of lines.

(2) On the premise that the maximum load rate of each line is not more than 50%, the medium-voltage network can be used to transfer the full load of a line to the interconnected opposite substation, when the extreme failure of a whole substation occurs.

(3) This structure can simplify the dispatch control strategy arrangement. According to the practical conclusion of distribution automation, on the premise that the maximum load rate is not more than 50%, the single-tie line is conducive to the scheduling control strategy arrangement, and it is good for the self-healing of distribution network.

(4) Simple and single structure is convenient for equipment maintenance. It can also fundamentally save equipment procurement costs and improve investment economy.

Therefore, in the mesh planning of urban distribution network, single radiation line should be transformed into single connection line, and complex connection line should be simplified into single connection line.

According to the relevant national standards, important power users should try to avoid using single power supply mode [15]. Therefore, in industrial parks and urban central areas with more important power users, in order to meet the double power demand, while ensuring that there is no cross-supply between power supply units, there are three types of a power supply unit: two pairs of overhead single-tie lines, two single-loop cable networks or one double-loop cable network, and link between different substations is recommended. As shown in Figures 2, 3 and 4.

Figure. 2 A power supply unit formed by two pairs of overhead single-tie lines [16]

Figure. 3 A power supply unit formed by two single-loop cable networks [16]
Figure. 4 A power supply unit formed by one double-loop cable network [16]

In urban area, a typical power supply mesh is shown in Figure 5. Load 1 is a first-class important power user [15]. According to the design requirements, the prime and standby power supply is planned to come from different buses of substation A. Load 2 is a secondary class important power user, and according to the design requirements, the double circuit from substation B is planned to be its two power sources. Load 3 is a prime class important power user, according to the design requirements, the prime power supply is planned to be substation C and the standby power supply to be substation A from the other direction.

Figure. 5 Typical Target Network Structure of a Power Supply Mesh to Satisfy Double Power Supply Users
2.3. Analysis of power supply reliability
The causes of power outage include three categories: planned power outage, power outage caused by power limitation and power outage caused by faults. In China, the commonly used index is the average power supply reliability index ASAI (%). The calculation formula is as follows:

\[
ASAI = \frac{\sum n_i TiNi}{n} \times \frac{8760n}{8760} \quad (1)
\]

Among them, \( n \) is the total number of users in the region, \( Ti \) is the outage time of load point \( i \), and \( Ni \) is the number of users of load point \( i \).

With the development of China's power grid, the proportion of power outage caused by power limitation is decreasing, but the planned outage of non-power limitation factors are still the main cause of power outage. With the improvement of operation and maintenance management of distribution network, the planned outage time of non-limiting factors decreases gradually, while the application of distribution automation system reduces the impact of outage due to fault.

Different wiring modes of medium voltage lines and different failure rates of overhead and cable lines are all factors affecting the reliability of power supply. It is shown in some literatures [17-18] that those three wiring modes, i.e. overhead single-link line, cable single-loop network and cable double-loop network, can meet the different power supply reliability requirements of urban and rural areas, by means of reasonable power line segmentation, adoption of distribution automation system and coordination of relay protection [16].

3. Case study
This paper has been successfully applied to the planning of medium-voltage power grid in many cities in Hubei Province of China. Taking the mesh planning of a city center as an example, the application of the mesh planning optimized method for areas with high reliability is expounded.

3.1. Data collection
The power supply area of the city center is 40 square kilometers, including 2 220kV substations and 8 110kV substations. There are 100 10kV lines. In 2018, the maximum power load was 219.67 MW, and the total society power consumption was 997 million kWh. During the 13th Five-Year Plan period, the growth rates of load and power consumption were 7.2% and 10.5% respectively. There are six important power users in this area, including public security bureaus, TV stations, hospitals and so on. Detailed data are shown in Tables 1 to 4.

### Table 1. Current situation and grid planning of substations in this area

| Voltage level (kV) | 2018 | 2020 | load saturation year |
|-------------------|------|------|----------------------|
| 220 110 35 Total  | 220  | 110  | 35 Total             |
| Number of substations | 2    | 8    | 10                   |
| Number of main transformers | 3    | 13   | 16                   |
| Substation capacity(MVA) | 510 552 | 510 602 | 690 1152 |
| Number of 10kV line interval | 24 154 | 24 166 | 190 33 298 331 |

### Table 2. Medium voltage equipment table

| Ring main unit room | Cabinet/pad-mounted distribution | pole-mounted transformer | Public distribution transformer | Private distribution transformer |
|---------------------|---------------------------------|--------------------------|--------------------------------|---------------------------------|
| number(MVA) | number(MVA) | number(MVA) | number(MVA) | number(MVA) | number(MVA) | number(MVA) | number(MVA) |
| 286 | 280 | 238 | 130 | 725 | 207 | 1431 | 618 | 1114 | 559 |
Table 3. Medium voltage network structure table

| Overhead network | Cable network |
|-----------------|--------------|
| Number of lines | Ratio of Multi-links lines(%) | Ratio of single-link lines(%) | Ratio of Radiant lines(%) | Number of lines | Ratio of double-loop network(%) | Ratio of single-loop network(%) | Ratio of double-shot (%) | Ratio of single-shot (%) | Ratio of other structure(%) |
| 82              | 28            | 49                           | 23                           | 18              | 0                                | 44                           | 0                            | 39                           | 17                           |

Table 4. Operation data of medium voltage network

| Number of 10kV lines | Number of 10kV lines which have links between substations | Ratio of links between different substations(%) | Transferable load between substations(MW) | Max load of substations(MW) | Transfer capability(%) | Ratio of Heavy Load Lines(%) | Ratio of overload lines(%) |
|---------------------|---------------------------------------------------------|---------------------------------------------|---------------------------------------|---------------------------|------------------------|----------------------------|----------------------------|
| 100                 | 63                                                      | 63                                         | 115.32                                 | 219.35                    | 52.57                  | 3                          | 0                          |

3.2. Divide power supply mesh
According to step (2) in section 2.1, the city center is divided into eight power supply meshes, as shown in table 5.

Table 5. Power supply mesh division

| Name of mesh | Size of mesh(km²) | Number of 10kV lines |
|-------------|-------------------|----------------------|
| Mesh 001    | 2.54              | 8                    |
| Mesh 002    | 2.59              | 12                   |
| Mesh 003    | 3.05              | 17                   |
| Mesh 004    | 2.97              | 14                   |
| Mesh 005    | 16.77             | 10                   |
| Mesh 006    | 2.49              | 10                   |
| Mesh 007    | 5.49              | 15                   |
| Mesh 008    | 4.09              | 14                   |

3.3. Current situation analysis of power grid
Take Mesh 003 as an example. The mesh includes 9 10kV lines from a 110kV substation and 8 10kV lines from a 220kV substation, totally 17 lines, with a maximum load of 33.96 MW. In 2018, the network interconnection relationship is complex, there are many extra links between lines within the same substation, and the load distribution among lines is unreasonable.

3.4. Load forecasting
Mesh 003 is mainly residential and commercial land, and is built-up area. The maximum load of mesh 003 is 33.96 MW in 2018, and is expected to reach 37.49 MW in 2020 and 50.88 MW in the saturated year.

3.5. Target network structure planning and power supply unit division in Mesh 003
Based on saturated load forecasting, the target network structure planning of 10kV trunk line is carried out in every mesh. To the saturated year, there will be 20 10kV lines in Mesh 003, including seven single-loop cable networks and three pairs of overhead single-link lines. The load of each line shall not exceed 4MW. When a fault occurs, it shall not exceed 8MW after the load transferred from the opposite line.

Based on this target network structure, Mesh 003 is divided into four power supply units, as shown in table 6, and the load is distributed into each power supply unit, as shown in table 7.
Table 6. Target network structure plan to saturated year of power supply unit

| Name of power supply unit | Target network structure |
|--------------------------|--------------------------|
|                          | cable double-loop network |
|                          | cable single-loop network |
|                          | overhead single-link |
| Mesh 003 Unit 001        | 0                        | 2                        | 0          |
| Mesh 003 Unit 002        | 0                        | 2                        | 0          |
| Mesh 003 Unit 003        | 0                        | 3                        | 0          |
| Mesh 003 Unit 004        | 0                        | 0                        | 3          |

Table 7. Load forecasting of power supply unit

| Name of power supply unit | Max Load in 2018(MW) | Max Load in 2020(MW) | Max Load to saturation year(MW) |
|--------------------------|----------------------|----------------------|---------------------------------|
| Mesh 003 Unit 001        | 8.66                 | 9.56                 | 12.98                           |
| Mesh 003 Unit 002        | 8.32                 | 9.18                 | 12.46                           |
| Mesh 003 Unit 003        | 8.89                 | 9.81                 | 13.32                           |
| Mesh 003 Unit 004        | 8.09                 | 8.93                 | 12.12                           |
| total                    | 33.96                | 37.49                | 50.88                           |

3.6. Make the transition plan of every power supply unit

Taking Mesh 003 Unit 001 as an example. The power supply area in the unit is 1.43 km² and the target structure is cable single-loop network. There are both structural problems and development problems in this unit now. Firstly, there are unreasonable segmenting and extra links in Line 001 and Line 003, and single radiation problem in Line 002 and Line 004. Secondly, there is new load demand in the future, while overload in Line 003 yet. The transition plan and solutions for each line is as shown in table 8.

Table 8. Transition plan of mesh 003 unit 001

| Name of lines | Current structure | problems | Transition structure | solutions |
|---------------|-------------------|----------|----------------------|-----------|
| Line 001      | Non-standard structure | 1. extra links | cable single-loop network | 1. complex interconnection changed into single connection between different substations/buses. 2. Increase the sectional switch |
|               |                    | 2. unreasonable segmenting |                     |           |
| Line 002      | Non-standard structure | single radiation line | cable single-loop network | single radiation line transforms into single connection line |
| Line 003      | Non-standard structure | 1. extra links | cable single-loop network | 1. complex interconnection changed into single connection between different substations/buses. 2. single connection between different substations and transfer load to the opposite line |
|               |                    | 2. overload |                     |           |
| Line 004      | Non-standard structure | single radiation line | cable single-loop network | single radiation line transforms into single connection line |

3.7. Distribution automation planning and corridor planning.

According to the target network and transition plan, a new cable trench of 8.7 kilometers is needed for Mesh 003.
3.8. Project Effectiveness Expectation

Figure 6. The structure of mesh 003 in saturated year

After the implementation of the plan, the network structure of mesh 003 is as Figure 6, and the improvement of each indicator in mesh 003 is as Table 9.

Table 9. improvement of indicators in mesh 003

| year          | Network structure | Equipment Level(%) | Power supply capacity(%) | performance index(%) |
|---------------|-------------------|--------------------|--------------------------|----------------------|
|               | Ratio of connection(%) | Average Radius of 10KV Line(km) | Average Segmentation Number of 10KV Lines | Ratio of 10KV cable lines | Average Maximum Load Rate of 10KV Lines | Average Load Transfer Ratio of Substation | Reliability of power supply | voltage qualification rate | Line loss rate |
| 2018          | 88.24             | 2.62               | 3                        | 23.98                | 24.32                 | 52.57                              | 99.9421                    | 99.983                     | 5.87          |
| 2020          | 100               | 2.65               | 3.5                      | 25                   | 25.73                 | 100                                | 99.9917                    | 99.99                     | 5.37          |
| saturated year| 100               | 2.43               | 4                        | 30                   | 29.88                 | 100                                | 99.9963                    | 99.99                     | 4.57          |

4. Conclusions
Based on the current work on mesh planning of distribution network, this paper proposes an optimization method of mesh planning to meet the demand of high reliability power supply in urban area. The main conclusions are as follows:

(1) The process of mesh planning is optimized, and the power supply mesh division and power supply unit division are taken as two steps in turn. After obtaining the power grid information, the power supply mesh is divided, while the power supply unit is divided after load forecasting and target network structure planning. Following this sequence, the problem of cyclic adjustment of mesh and unit division can be avoided. After the mesh is determined, it is generally unsuitable to change, while the division of power supply units can be rolling revised according to the municipal planning.

(2) A target network structure and power supply unit division model for medium-voltage power grid is proposed, which is suitable for industrial parks with more important power users and urban areas with higher power supply reliability requirements. It can meet the double power demand of important power users and ensure that there is no cross-supply between power supply units. The power supply range of the model is clear, and the grid structure is concise, which is conducive to the
maintenance management. At the same time, the practice of distribution automation system shows that the structure is conducive to the scheduling control strategy arrangement, thereby improving the reliability of power supply.

(3) Examples show that the method is practical and operational. The process flow is clear, the recommended network structure is concise, and it gives consideration to maintenance and dispatching at the very beginning of power grid plan. Therefore, it is very useful for the power engineering field, and the planning results are concise, reliable and economical.

(4) Due to the limitation of the paper, the method presented in this paper can be applied to areas with high reliability power supply demand in urban power grid. How to design differentially in rural areas needs further research in the future.

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