Research on Coordinated Power Supply Mode of Multi-voltage Level Distribution Network Considering Reliability

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Abstract. In order to address that current coordinated power supply research of distribution networks only considers single voltage level, coordinated power supply modes for multi-voltage distribution networks considering 110kV lines are established, and optimized based on economic performance and load supply capability. Firstly, based on the connection modes of distribution lines, interconnecting structure of substations and allocation of transformers, the typical power supply modes for medium-voltage distribution networks are constructed, and the mode attributes are calculated. Then, based on economic analysis and load supply capability, the optimal match mode and mode parameters for network/substation on different voltage levels are selected with the objective of minimizing load supply cost. Finally, 110kV distribution networks are introduced, and the power supply relations between 110kV lines and 110kV transformers are studied, and the optimal coordinated power supply mode for multi-voltage distribution networks considering 110kV lines is obtained, which can provide guidance for the coordination and planning of regional distribution networks.

Keywords: coordinated power supply mode; reliability; multiple voltage levels.

1. Introduction

As the last link of the power system to power users, the distribution network has the closest relationship with power users. With the continuous development of the national economy, there is a big contradiction between the increasing shortage of land resources and the rapidly rising demand for electrical energy, which has brought more constraints on the planning and coordination of the distribution network. Carrying out the coordinated power supply of the multi-voltage level distribution network can not only improve the utilization rate of power equipment, but also reduce the land resources occupied by the distribution network construction [1-3].

The multi-voltage level distribution network includes a 110 (35) kV high-voltage distribution network, a 110 (35) kV substation, a 10kV medium-voltage distribution network, a 10kV distribution transformer, and a 380 (220) V low-voltage feeder network. However, because the 380 (220) V low-voltage distribution network usually has a radial structure, it can hardly provide support in the event of a 10kV medium-voltage distribution network failure. Therefore, the study of coordinated power supply in multi-voltage grade distribution networks does not take this into consideration. In the field of
coordinated power supply research, the literature [4] analyzed the economics and reliability of several common medium-voltage distribution network wiring modes, and gave the applicable scenarios of different wiring modes; reference [5] further discussed the urban power distribution. The wiring modes of the 110kV high-voltage distribution network and the 10kV medium-voltage distribution network in the network have been compared for economy and reliability. However, the network wiring modes of each voltage level studied by the two are too simple, and are limited to the current level of the distribution network. The contact mode fails to reflect the coordinated power supply relationship of the distribution network covering multiple voltage levels. Literature [6] proposed a comprehensive power supply scheme for medium-voltage distribution networks, but did not involve high-voltage distribution lines. It can be seen that the current research on coordinated power supply for distribution networks only considers coordination between distribution networks below 110kV, and does not involve 110kV high-voltage distribution lines.

To this end, this paper first constructs a typical power supply mode of a distribution network below 110kV considering a 10kV distribution network and a 110kV substation, and calculates the attribute parameters of each power supply mode based on the equipment load factor of each voltage level. Second, analyze the external characteristics of each power supply mode, including economy and load capacity. Then, taking the unit load cost of the distribution network as the goal, the best parameters of the distribution network and substations with different voltage levels are selected. Finally, the power supply relationship between the 110kV distribution network and the 110kV main transformer is studied, and the optimal coordinated power supply mode of the multi-voltage level distribution network considering the 110kV distribution network is obtained, which provides guidance for the coordination and planning of the future distribution network.

2. Basic Concept of Power Supply mode and Division of Research Scope

2.1. Basic Concept of Power Supply Mode

Definition 1 Power supply mode:. Refers to the combined power supply method based on the interconnection structure of the substation and the network connection mode. This article covers 110kV high-voltage distribution network to 10kV medium-voltage distribution network, and can also include 0.4kV distribution network.

Definition 2 Substation interconnection structure: refers to the interconnection structure of 110kV substations as the power source of the medium voltage distribution network, which is mainly affected by the regional characteristics and load characteristics of the power supply area.

Definition 3 Network connection mode: refers to the interconnection of 110kV high-voltage distribution lines and 10kV medium-voltage distribution lines in the distribution network [6].

2.2. Research Scope

Considering that the 110kV high-voltage distribution line is very different from the 10kV medium-voltage distribution line in the connection mode, this paper takes the 110kV substation as the boundary, and first establish a power supply mode for the distribution network below 110kV (including the 110kV substation), and then based on this Consider 110kV high-voltage distribution lines.

3. Construction of Power Supply Mode for Distribution Networks below 110kV

The distribution network power supply mode below 110kV refers to a power supply unit that uses a 110kV substation as the source and a 10kV distribution line as the network. This part of the power supply mode includes the interconnection structure of the substation and the network wiring mode. The interconnection structure of the substation involves the contact structure of the main transformer of the 110kV substation, the network wiring mode involves the main wiring of the 110kV main transformer low-voltage side and the 10kV distribution network wiring mode. At the same time, the network wiring mode will also be affected by the main transformer configuration of the substation.
3.1. Substation Interconnection Structure

Generally speaking, the more the number of substations that communicate with a substation, the more substations that provide load transfer support when the main transformer fails and is out of service, so that the main transformer and even the substation can be improved. Load capacity of the entire distribution network. However, with the increase in the scale of the interconnection of substations, the improvement of the load capacity of the distribution network will no longer be obvious. Therefore, although increasing the scale of substation interconnection can improve the maximum load capacity of the distribution system, combined with economic analysis, it can be seen that the economic benefits of substation interconnection and the improvement of load capacity will not be obvious after the interconnection scale reaches 4 [7]. Therefore, the interconnection structure of the substation includes single-station, two-station, three-station and four-station interconnections, and correspondingly forms a point, chain, triangle and quadrangular power supply architecture [8]. Because there is only one substation power supply scenario in the point power supply architecture, and it does not involve the problem of multiple substations providing transfer support, this article will not consider the point power supply architecture.

3.2. Substation Main Transformer Configuration

According to the technical guidelines for urban distribution networks, each 110kV substation is usually configured with two main transformers and three main transformers. Among them, the configuration of the two main transformer substations is mainly used in the initial construction phase of the regional power distribution network [8]. At this stage, the regional load is relatively small, and the two main transformer substations can meet the user load demand of the power supply area. As the load increases, the regional distribution network gradually enters the stage of development and improvement, and the load will exceed the load capacity of the two main transformer configuration model, so the three main transformer configuration needs to be finally reached. Considering that this paper mainly studies the coordinated power supply mode in the long-term period, at this stage, the regional distribution network has entered the stage of development and perfection, so each of the 110kV substations in this paper is equipped with three main transformers.

3.3. Network Wiring Mode Type

The network wiring mode involves 110kV main transformer low-voltage side main wiring and 10kV network wiring mode. Because the number of main transformer substations will affect the low-voltage side main wiring, it is necessary to analyze the low-voltage side wiring according to the different sub-scenes of the number of main transformer substations: the low-voltage side main wiring of the two main substations uses single-parent section wiring; The main wiring includes single-bus four-segment and single-bus six-segment ring wiring [9]. In the case of a self-cut and continuous jump device, the maximum load capacity of the 110 (35) kV main transformer under the two types of wiring is the same, but the former is low in cost. Therefore, a single bus four-section connection mode with a self-cut and continuous jump device should be used. ; The main wiring of the low-voltage side of the four main transformer substations includes single-mother section wiring and four groups of single-mother section ring wiring for each two main transformers [9].

The 10kV network wiring mode includes overhead single radiation, overhead multi-segment moderate contact, cable single ring network, cable double ring network, main and standby wiring, etc. For the "3-1" and "4-1" main and standby wiring modes, if the wiring is based on the typical power supply mode, the average utilization of the line in the station is not essentially different from the two and three connections. Therefore, this article divides them into two contacts and three contacts, and does not explain them separately. According to the connection relationship between the lines, it can be further summarized as single radiation, single connection, two connections, and three connections. Due to the consideration of the area width and the corridor corridor, the medium voltage distribution lines in the chain power supply model do not use three connections. Wiring mode.
3.4. Power Supply Mode Construction
In order to simplify the analysis level, this paper also merges the number of interconnected substations in the power supply mode with the configuration of the main transformer substation to form two “substation-main transformer” combined modes of $2 \times 3, 3 \times 3, 4 \times 3$. The basic structure of the distribution network power supply mode below 110kV that simplifies the difference in the number of main transformers is shown in Table 1.

Table 1. Power supply modes below 110kV

| Type       | Single contact | Two contact | Three contact |
|------------|----------------|-------------|---------------|
| Chain      | ![Chain Single] | ![Chain Two] | ![Chain Three] |
| triangle   | ![Triangle Single] | ![Triangle Two] | ![Triangle Three] |
| square     | ![Square Single] | ![Square Two] | ![Square Three] |

4. Properties and Calculation of Power Supply Mode

4.1. Power Mode Properties
The construction of the above power supply model only gives the structure of the power supply mode from the perspective of graph theory, which is far from enough for how to select and apply the power supply mode in actual planning. It is necessary to further study the attributes of the power supply mode, to obtain precise quantitative indicators, and to provide guidance for the selection of power supply modes.

The attribute of the power supply mode refers to the inherent characteristics of the power supply mode [9]. In this paper, the basic attributes of the power supply model include the average load rate of the main transformer, the theoretical load rate of the line, and the number of power supply units of the model feeder.

4.2. Calculation Method of Power Supply Mode Attributes
The formula for calculating the average load rate of the main transformer is:

$$T = \min \left\{ \frac{KS(N-1)}{NS} \times 100\%, \frac{(mN-1)S}{nNS} \times 100\% \right\}$$

In the formula, $T$ is the average load rate of all the main transformers in the power supply mode, $N$ is the number of main transformers in the station configured in a substation, $S$ is the rated capacity of a main transformer in the substation, $K$ is the overload coefficient of a main transformer in the substation, $n$ is the number of substations in the model.

The calculation formula of the theoretical line load ratio is:

$$\eta = \frac{mS_0}{(m+1)S_0} \times 100\%$$

In the formula, $\eta$ is the maximum load rate of all lines in the power supply mode, $m$ is the number of contacts of a single line, and $S_0$ is the line capacity corresponding to the line model.

The number of power supply units of the mode feeder can be obtained by keeping the load of the main transformer of the substation consistent with the load of the output line of the transformer. The load of the main transformer can be characterized by the average load rate of the main transformer, and
the load of the medium voltage output line can be used by the theoretical load rate of the line. Characterization. This paper adopts the method of calculating the number of power supply units of the model feeder proposed in [9].

4.3. Calculation Result of Power Supply Mode Attribute
Due to space limitations, this article only gives the attributes of the power supply mode under specific conditions. The attributes of the power supply mode under other conditions can be obtained by similar methods and processes. In this article, the specific distribution network boundary conditions are as follows: 1) the capacity of the main transformer: the capacity of each main transformer is 50MVA; 2) the power factor: the power factor of the main transformer is 0.95, the line power factor is 0.90; 3) the overload factor: The main transformer is allowed to be overloaded for a short time, and the overload coefficient is 1.3; 4) Line selection: For overhead lines, JKLYJ-240 lines are uniformly selected, and the line capacity corresponding to the line safe current limit is 10.05MVA.

Based on the above calculation method, the attributes of the power supply mode in the combination mode of the above three types of substations and the main transformer configuration mode for the medium-voltage distribution line using single-link, two-link, and three-link wiring modes can be obtained, as shown in Table 2.

| Combination mode | Wiring mode | Load factor (%) | Line theoretical load factor (%) | Number of outgoing lines on low-voltage side of substation | Number of power supply units inside the station | Number of power supply units between stations |
|------------------|-------------|----------------|---------------------------------|--------------------------------------------------------|---------------------------------------------|-----------------------------------------------|
| 2×3              | Single contact | 83.3% | 50% | 50% | 54 | 22 | 5 |
|                  | Two contacts  | 83.3% | 50% | 66.7% | 48 | 16 | 4 |
|                  | Single contact | 88.9% | 50% | 50% | 84 | 27 | 15 |
| 3×3              | Two contacts  | 88.9% | 50% | 66.7% | 72 | 15 | 9 |
|                  | Three contacts | 88.9% | 50% | 66.7% | 60 | 6 | 9 |
|                  | Single contact | 91.7% | 50% | 50% | 116 | 40 | 18 |
| 4×3              | Two contacts  | 91.7% | 50% | 66.7% | 96 | 20 | 14 |
|                  | Three contacts | 91.7% | 50% | 66.7% | 96 | 20 | 14 |

4.4. Power Supply Mode Characteristics
As the external characteristics of the power supply mode, the characteristics of the power supply model can measure the performance of the power supply mode in terms of load capacity, reliability, power quality, and economy [6]. Considering that the optimization of the distribution network coordinated power supply mode needs to solve the problem of measuring indicators and evaluation methods for describing the degree of coordination, the ultimate purpose is to find the most economical investment under the premise of meeting the system's safe operation constraints and load requirements. Model to maximize the load capacity of the distribution network. Therefore, the determination of the optimal power supply mode requires comprehensive consideration of both economics and load capacity. This article is based on the life cycle cost, only the construction cost is considered in the cost calculation, and the unit load cost is used as the objective function to optimize the above power supply mode.

The calculation method of the load capacity is referred to [10]. The calculation result of the load capacity of the above power supply mode is shown in Figure 1. In the economic evaluation of the power supply mode, the full life cycle cost is used, including the cost of distribution network construction, operation and maintenance, and investment residual value, of which the construction cost accounts for the largest proportion. Therefore, only the construction cost of the distribution network is considered in the simplified estimation in this paper. According to [11], the construction cost of the 2 * 50MVA substation is 35 million yuan / seat; the construction cost of the 3 * 50MVA substation is 50 million yuan / seat.
yuan / seat; Based on the line construction principles, the typical length of a 10kV medium voltage distribution line is 2.4 km [10].

The unit load cost of the above power supply mode is shown in Figure 1.

![Fig. 1 Cost calculation results of power supply models](image)

As can be seen from Figure 3, when three 110kV substations are interconnected, each station is equipped with three main transformers to form a “3 × 3” substation interconnection mode, and the 10kV distribution network uses three-contact wiring. The lowest is 681,000 yuan / MVA, which has reached the goal of increasing the load capacity of the distribution network while reducing construction costs.

5. Consider the power supply mode of 110kV distribution network

As a bridge connecting the upper and lower power grids, the 110kV distribution network provides an important way for the upper 220kV power supply to supply the lower 110kV distribution network. Its connection relationship with the lower 110kV substation directly affects the coordinated power supply of the distribution network. Therefore, the power supply relationship between the 110kV distribution line and the 110kV main transformer needs to be studied.

If the same 110kV distribution line supplies multiple 110kV main transformers at the same time, and whether these main transformers belong to the same 110kV distribution network power supply mode or not, the load capacity of the distribution network will be affected differently when the 110kV distribution line fails. Considering the failure at the exit of the 110kV distribution line, the load it brings can only be transferred through the lower-level distribution network. According to whether the main transformer supplied by the 110kV distribution line belongs to the same distribution network power supply mode below 110kV, analyze the load capacity of the distribution network under different power supply modes.

If multiple 110kV main transformers powered by a 110kV distribution line belong to different power distribution modes of the distribution network below 110kV, as shown in Figure 2, it is recorded as scenario 1. When the distribution line is out of service, it is equivalent to In the independent power distribution mode of the distribution network below 110kV, the load transfer of the main transformer “N-1” is performed separately. Through the analysis of the typical power supply mode of the 110kV substation and the distribution network below, it can be seen that the lower-level distribution network has the same distribution network below 110kV Load transfer capacity of the main transformer “N-1” in the power supply mode. Therefore, in this scenario, the load transfer is smooth and the system can reach the maximum load capacity;

![Fig. 2 Scenario 1](image)
If multiple main transformers powered by a 110kV distribution line belong to the same 110kV distribution network power supply mode, as shown in Figure 3, recorded as scenario 2, when the line is out of service, it is equivalent to the same 110kV distribution Loss of two or three main transformers at the same time in the power supply mode of the power grid, that is, performing the "N-2" or "N-3" verification of the main transformer in the same power supply mode of the distribution network below 110kV will inevitably cause difficulty in load transfer. The overall load capacity of the system is reduced.

Fig. 3 Scenario 2

Based on the above analysis, it can be known that multiple 110kV main transformers powered by a 110kV distribution line should belong to different power supply modes of the distribution network below 110kV, which can ensure the overall load capacity of the system.

6. Conclusion
In this paper, through the study of coordinated power supply schemes for distribution networks, a multi-level distribution network coordinated power supply model considering 110kV distribution lines, 110kV substations, and 10kV distribution lines is established, and the following conclusions are obtained: Distribution networks below 110kV Medium, 110kV substations are recommended to use three substation interconnection structures, each station is equipped with three main transformers to form a "3 × 3", single-bus four-segment wiring mode is recommended for the low-voltage side of 110kV substations, and 10kV medium-voltage distribution networks are recommended. Three-phase connection wiring mode; and, multiple 110kV main transformers powered by the same 110kV power distribution line should belong to different power distribution modes below 110kV. This conclusion can be used to guide the establishment of a coordinated power supply mode for the distribution network.

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