Research on the flex network structure for testbeds of distribution system

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Abstract. Objective: The real distribution network testbed is a testing and experiment environment for the popularization and application of new technologies, new equipment and new methods in distribution network. In order to simulate the operation of the actual distribution network as much as possible, the grid structure of the real testbed should be consistent with the actual distribution network. However, due to site conditions and investment constraints, the construction of a flexible grid structure and the conversion of different connection modes through the on-off configuration of distribution switches is the key to the construction of real distribution network testbed. Methods: This paper analyzes the structural characteristics of typical connection modes of domestic 10kV distribution lines, puts forward the decomposition and reconstruction method of typical connection modes based on unit structure, and then puts forward the grid structure of real distribution network testbed which can be switched flexibly. Results: By using the grid structure, the typical connection modes of all kinds of cables, overhead and hybrid lines, as well as the atypical connection modes with branch lines can be flexibly switched, which can meet the requirements of all kinds of tests and experiments of the real distribution network testbed. Conclusion: Based on the actual engineering example, the method proposed in this paper is scientific and effective, and provides method support for the construction scheme of real distribution network testbed.

Keywords: distribution network, real testbed, grid structure
1. Introduction
At present, there are great limitations in the accuracy of the results in the verification of the new technology and equipment of the distribution network by means of laboratory digital simulation and low-voltage dynamic simulation, while the trial operation of the equipment is limited by the application environment [1]. The real distribution network testbed is a real testing site for all kinds of testing and verification[2]. It adopts real primary and secondary equipment, control system and communication system, as well as a grid structure that can be consistent with the reality[3,4]; it makes all kinds of transient processes of distribution network consistent with reality, and provides platform conditions for the verification and experimental research of new technology, performance and environmental adaptability of new equipment[5-8]. At present, the State Grid Corporation has built or is building real distribution network test sites of different sizes in Luohe of Henan, China Electric Power Research Institute (Wuhan), Jiangsu Electric Power Research Institute, Shandong Electric Power Research Institute, Shaanxi Electric Power Research Institute, Jiangxi Electric Power Research Institute, Hubei Electric Power Research Institute, Jinhua of Zhejiang and other places, and several advanced power companies abroad, such as First Energy Corporation in the United States, have also built corresponding test sites.

The grid structure is the basis of all kinds of testing and verification, and is closely related to the transient characteristics of the real testbed. Therefore, in order to simulate the operation of the actual distribution network as much as possible, the grid structure of the real testbed should be consistent with the actual distribution network. According to the technical standards such as “Technical Guide for Enhancement of Medium- and Low-voltage Distribution Networks, DL/T 599-2016” and “Technical Guide for Distribution Network Planning of 110kV and Below by China Southern Power Grid”[5], typical distribution network connection modes include single-radiation, “N-1” single-ring network, N-segment n-connection, N supply-backup, double-ring network, and so on. In the actual distribution network, there are also atypical connection modes such as large branches, second and third branches, and so on. However, due to site conditions and investment constraints, the real testbed is obviously unable to build a set of feeders for various connection modes.

For this reason, this paper analyzes the structural characteristics of typical connection modes of domestic 10kV distribution lines, puts forward the decomposition and reconfiguration method of typical connection modes based on unit structure, and then puts forward the grid structure of real distribution network testbed that can be flexibly switched, thus realizing the reconstruction and conversion of different connection modes through the on-off configuration of distribution switches and meeting the requirements of all kinds of tests and experiments of real distribution network testbed. The purpose of this paper is to provide method support for the construction scheme of real distribution network testbed.

2. The connection modes of 10kV distribution network
The connection mode of the distribution line actually reflects the contact relationship of the lines. Medium voltage distribution network consists of a mixture of overhead lines and cable lines.
Although the specific connection modes of overhead network and cable network are different, it can be divided into six types of connection modes from the point of view of contact relationship: single-radiation, single-connection, double-ring network, two connections, “N-1” main and standby connection and so on.

2.1. single-radiation connection

The single-radiation connection modes of overhead and cable networks are shown in Fig. 1:

![Single-radiation connection of overhead network](image1)

(a) Single-radiation connection of overhead network

![Single-radiation connection of cable network](image2)

(b) Single-radiation connection of cable network

**Figure 1.** Single contact connection modes

For this simple connection mode, there is no load transfer after a line fault, so the spare capacity of the line can be ignored, that is, each outlet (trunk line) can run at full load.

2.2. Single connection connection

The single-connection connection mode of the overhead network and the cable network and its derivative connection mode are shown in Fig. 2:

![Overhead line](image3)

(a) overhead line

![Cable line](image4)

(b) cable line

**Figure 2.** Single contact connection modes of cable line
The greatest advantage of this connection mode is that compared with the single-radiation connection mode, the reliability has been greatly improved, and at the same time, the connection is clear and the operation mode is simple. In the case of line failure or power failure, under the condition that the line load allows, the power supply of the non-fault section can be restored through the switching operation, and the line load rate can reach 50% in the case of “N-1” check.

2.3. N supply-backup connection

N supply-backup connection is generally used for cable network, which mainly means that n cable lines are connected into a cable ring network, of which one line is idle and the rest are running at full load. The main and standby connections of the cable network “3-1” are shown in Fig. 3.

![Figure 3. Three-supply and one-backup connection of cable network](image)

In this connection mode, if a certain operating line fails, the standby line can be put into operation by line switch. With the difference of \( n \) value, the operation flexibility, reliability and average load rate of the connection are different.

2.4. Double-ring network connection

From the point of view of the contact mode, the double-ring network connection is also the single-contact connection, and the difference between the double-ring network connection and the single-connection lies in the different user access mode. Double-ring network connection has high power supply flexibility, which can maximize the continuous power supply to users and meet the dual power supply requirements of important users. The connection mode of the double-ring network is shown in Fig. 4:

![Figure 4. Cable double-ring network connection](image)

2.5. Two contact connection

The two connection connection modes of the overhead network and the cable network and their
derivative connection modes are shown in Fig. 5 and Fig. 6:

![Figure 5. Two-stage and two-contact connection of overhead network](image1)

![Figure 6. Two-stage and two-contact connection of cable network](image2)

The biggest advantage of this connection mode is that because each line has a power supply connected with it, when any line fails, it will not affect the normal power supply of other line sections, thus reducing the fault range of each line and improving the reliability of power supply. In addition, due to the large number of contacts, the utilization rate of the line is also improved, and the line load rate can reach 66.7% in the case of “N-1” check.

3. The definition of structural element and its derivation

3.1. Infrastructure element

Structural element refers to the smallest modular network unit that can no longer be divided in complex networks. In the process of operation, scheduling and fault recovery, the structural element expresses its characteristics as a whole. If the structural element is taken apart, the predetermined functional task will not be completed. The structural element can represent the main characteristics of the whole network. It is also a small network, and the whole network is composed of the same or different structural elements.

The connection of medium voltage distribution network is divided into three levels: system, family and structural element [3]. In medium voltage distribution network, various connection modes can generate any homologous connection mode [4] through the derivation of structural elements. Therefore, the structural elements of the above six types of connection modes are compared and summarized. A flexible grid structure that can reconstruct different connection modes can be formed. The connection modes such as single-radiation, single-connection, double-ring network, two connection, “N-1” active and standby connection can be derived from single-radiation structure element. Therefore, for the real testbed, the key to constitute a flexible grid structure is to derive cable overhead hybrid connection through a single-radiation structural element, as well as other typical connections, that is, the two contact structural elements can be used as infrastructure elements for
other connection modes.

3.2. Derivation of infrastructure elements
Other wire connection modes can be derived from infrastructure elements, as shown in the following figure.

![Figure 7. Various connection modes derived from a single-radiation structural element](image)

4. Flexible grid structure
In the actual distribution network, there is often a distribution network structure of all kinds of cable-overhead line hybrid lines. Therefore, on the basis of the two contact structure elements shown in figure 6, it is necessary to build a new overhead line, which is juxtaposed with the cable line, and realize the mixing of the overhead line and the cable line through the switching operation of the switch. The structure diagram is shown in the following figure.

![Figure 8. Flexible grid structure of real testbed](image)

As shown in the figure, the flexible grid structure of the real testbed consists of four-circuit cable lines and two-return overhead lines. Through the switch switching operation, the reconstruction of different connection modes is realized.
4.1. Single radiation
A single-radiation line consisting of six-circuit cables or overhead lines can be formed by disconnecting the connection switches between lines T01triple T06 and G04, G10 and K05. In addition, a cable-overhead hybrid single-radiation line can be formed by using the contact switch, for example, 003, G07, G08, G09, G14, T05, K05, K06 and K07 are closed, while other switches remain open, a single-radiation circuit consisting of F3 and F6 is formed, as shown in the following figure.

![Figure 9. Cable overhead hybrid single-radiation connection](image)

4.2. Single contact
On the basis of the above single-radiation, the outlet switch of the opposite line is closed and one of the sectional switches is separated, which can be easily reconstructed into a single-connection connection. Taking F1 and F2 as examples, in 001,002 and G01–G06 switches, keeping G04 open and other switches closed, a single-connection connection composed of F1 and F2 can be formed.

4.3. Double-ring network
A double-ring network connection can be constructed through two single-connections. For example, a set of double-ring network connections is formed by using F1 and F2 to form a single-connection, F3 and F4 to form a single-connection, and T01, T02 and T03 are regarded as the bus switches of two user buses, respectively, forming a set of double-ring network connections, as shown in the following figure.

![Figure 10. Connection mode of double-ring network](image)

Similarly, if the single-connection composed of F5 and F6 is used instead of the single-connection of F3 and F4, the cable-overhead hybrid double-ring network connection can be formed.

4.4. N for one backup.
Both N supply-one backup and double-ring networks belong to the same kind of structural elements,
so the double-ring network can be reconstructed into N for backup by switching operation. For example, based on the double-ring network structure shown in figure 9, open the G05, G12 and 004 switches and close G03 and G09, as shown in the following figure.

![Figure 11. N supply-backup connection mode](image)

4.5. Atypical connection
Because there are six circuit lines in the grid, the other two circuits can be connected as long branch lines or divided into two branch lines to form atypical connection by forming a typical connection with four of them. As shown in the following figure, by closing G13, T04, K02, and G15, T06 and K06, two branch lines are connected to the original three supply and one backup connection, forming a common atypical connection mode of trunk plus branch lines.

![Figure 12. Atypical connection composed of three-supply one-backup plus branch lines](image)

5. Example analysis

5.1. The grid reconstruction modes
1) Single-radiation from overhead lines.
   Close the G09 cabinet switch, turn off the G02, G03, G04, G10, G11 cabinet switch, turn off the C609 switch of the outdoor switch box 3, and F4 form a single-radiation connection mode.

2) Single contact of 3.2.2 overhead line
   Disconnect the switches of the G02, G03, G04 and G09 cabinets, close the G10 and G11 cabinets, disconnect the A608 switch of the outdoor switch box 1, form a single-radiation connection mode,
disconnect the B608 switch of the outdoor switch box 2, and disconnect the C608 switch of the outdoor switch box 3 to form a single-radiation connection mode. F5 and F6 form an overhead line single contact connection mode.

3) Large branch of single-radiation band

Turn off the G02, G03, G04, G09, G11 cabinet switch, close the G10 cabinet switch, turn off the A605 switch of the outdoor switch box 1, close the A608, A609 switch, turn off the B605 switch of the outdoor switch box 2, close the B606, B609 switch, turn off the C605 switch of the outdoor switch box 3, close the C606 switch, and turn off the C609 switch. F5 forms a single-radiation belt with large branch model.

4) Single-contact band with large branch

Turn off the G02, G03, G04 and G09 cabinet switches, close the G10 and G11 cabinets, turn off the A605 switch of the outdoor switch box 1, close the A608 and A609 switches of the outdoor switch box 1, turn off the B605 switch of the outdoor switch box 2, close the B606 and B609 switches, and turn off the C605 switch of the outdoor switch box 3, close the C606 switch and turn off the C609 switch. F5 and F6 form a single contact zone with large branches.

5) N-segment n-contact

Turn off the G04 and G09 cabinet switches, close the G02, G03, G10, G11 cabinet switches, turn off the A605, A609 switches, A601 and A608 switches of the outdoor switch box 1, turn off the B601 and B605 switches of the outdoor switch box 2, close the B603 and B608 switches of the outdoor switch box 3, close the C601 and C603 switches of the outdoor switch box 3, and turn off the C605 and C608 switches of the outdoor switch box 3. F5 forms an N-segment n-contact connection mode.

6) 2-1 single-ring network

Turn off the G04, G09, G10, G11 cabinet switches, close the G02 and G03 cabinets, turn off the A605, A608 switches, A601, A603 switches of the outdoor switch box 1, turn off the B605, B608, B603 switches of the outdoor switch box 2, close the B601, C603 switches of the outdoor switch box 3, and turn off the C605, C608 switches of the outdoor switch box 3. F1 and F2 form a cable “2-1”
single-ring network connection mode.

7) 3-1 single-ring network

Disconnect the G09, G10, G11 cabinet switches, close the G02, G03, G04 cabinet switches, turn off the A605, A608 switches, A601, A603, A606, A609 switches of the outdoor switch box 1, turn off the B603, B605, B608, B608, B601, B606, B609 switches of the outdoor switch box 2, and turn off the C605, C608, C609 switches of the outdoor switch box 3. F1, F2 and F3 form the connection mode of “3-1” cable single loop network.

Figure 14. Schematic diagram of 3-1 single-ring network

8) 2-supply 1-backup cables

Turn off the G09, G10, G11 cabinet switches, close the G02, G03, G04 cabinet switches, turn off the A605, A608 switches of outdoor switch box 1, A601, A603, A606, A609 switches, turn off the B605, B608 switches of outdoor switch box 2, B601, B603, B606, B609 switches, and close the C603, C605, C608, C609 switches of outdoor switch box 3. F1, F2 and F3 form the cable two-supply and one-backup connection mode, in which F2 is the backup line.

9) 3-supply 1-backup cables

Switch off the G10 and G11 cabinets, close the G02, G03, G04, G09 cabinets, turn off the A605, A608 switches of the outdoor switch box 1, turn off the A601, A603, A606, A609 switches of the outdoor switch box 1, turn off the B605, B608 switches of the outdoor switch box 2, close the B601, B603, B606, B609 switches of the outdoor switch box 3, and turn off the C603, C605, C608 switches of the outdoor switch box 3. F1, F2, F3 and F4 form a three-supply and one-backup connection mode, in which F4 is a backup line.

10) Double-ring cable network

Switch off the G10 and G11 cabinets, close the G02, G03, G04, G09 cabinets, turn off the A605, A608 switches of the outdoor switch box 1, turn off the A601, A603, A606, A609 switches of the outdoor switch box 1, turn off the B605 and B608 switches of the outdoor switch box 2, close the B601, B603, B606, B609 switches of the outdoor switch box 3, and close the C603, C605, C606, C609 switches of the outdoor switch box 3. F1 and F2, F3 and F4 form a double-ring network connection mode.

6. Conclusion
New technologies and theories such as grounding fault analysis, neutral grounding mode research, distribution automation construction mode, new energy access impact analysis, and new distribution network protection are the main testing and verification projects carried out by the true testbed of distribution network at present, and the transient characteristics of the disturbance are closely related to the grid structure. Therefore, the grid structure of the real distribution network testbed must be consistent with the actual power grid as much as possible. Limited to long-term conditions and investment scale, the construction of a flexible grid structure and the conversion of different connection modes through the on-off configuration of distribution switches is the key to the construction of real distribution network testbed.

Based on the analysis of the structural characteristics of typical connection modes of domestic 10kV distribution lines, this paper puts forward the derivation and construction method of typical connection modes of medium voltage distribution network based on single-radiation structure element, and constructs the grid structure of real distribution network testbed which can be switched flexibly.

The calculation and analysis of practical examples show that the flexible grid structure proposed in this paper is scientific and effective. It can reconstruct single-radiation, single-connection, N-segment n-connection, N supply-backup, N-1 single loop network and cable double-ring network under overhead lines, cable lines and hybrid lines, as well as atypical connection with branch lines, which will provide method support for the construction of true testbed of distribution network.

References
[1] Zuo Bo. 10kV Distribution Network Simulation System Establishment and Performance Evaluation[D]. School of Electrical and Electronic Engineering, 2017.
[2] Cheng Weixin. The Improvement Design and Application of the True Value Distribution Network[D]. Hunan University of Technology, 2018
[3] Adapa R. Innovative techniques in modeling UPFC for power system analysis. IEEE Transactions on Power Systems: A Publication of the Power Engineering Society.2000,15(1).
[4] Jim Ledin. Simulation engineering[M]. USA: CMP Books, 2001:10-13.
[5] State Grid. DL/T 5729-2016, The Guide of Planning and Design of Distribution Network, DL/T 599-2016