METHODOLOGY   **Open Access**

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A diagnostic method for distribution networks based on power supply safety standards

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Abstract

In order to overcome the shortages of diagnostic method for distribution networks considering the reliability assessment, this paper proposed a method based on power supply safety standards. It profoundly analyzed the security standard of supply for urban power networks, and established quantitative indicators of load groups based on different fault conditions. Then a method suitable for diagnostic evaluation of urban distribution networks in China was given. In the method, "N-1" calibration analysis of the distribution network was conducted. Then the results are compared with quantitative indicators of load groups on different conditions deriving the diagnostic conclusions and the standard revision is discussed. The feasibility and accuracy of the method is finally verified in the case study.

Keywords: Distribution network, Diagnostic process, N-1 calibration analysis, Power supply security

Introduction

With the rapid development of social economy and continuous improvement of people's living standards, the terminal users of urban power networks require more secure and reliable supply [1]. Therefore, the major problem and technical difficulty the urban power networks are facing in China are how to invest moderately to meet the security and reliability of supply which can be accepted by the users [2]. To solve the technical difficulty, the primary task is finding an appropriate method to diagnose power grid structure and investigate the realistic condition of grid operation. At present, reliability assessment is usually used.

However, as the main method of security diagnosis, reliability assessment has many shortages. It mainly focuses on three aspects, which are the frequency, duration and range of interruptions. Reliability indexes can reflect supply condition at every point of the system [3]. At present, the frequency of interruptions mainly relies on statistics of people, which cannot realistically reflect the situation of the grid due to great personal factors.

Although the duration and range of interruptions can be obtained by the network, quantitative indicators are used to determine whether they comply with safety standards. Therefore, the criterion of supply security needs to be studied by utilizing the data sources and operational experience and basing on the practical situation of urban power networks, in order to provide the theoretical fundamentals and solutions of improving security of urban power networks in China.

To obtain the method of security diagnosis, this paper firstly analyses the basic concept on the safety standards of power supply and obtains the quantitative indicators by confirming the relevant regulations and evaluation index of "supply security". Then, a set of diagnostic evaluation method, which is suitable for Chinese urban distribution networks, is constructed based on these indexes and "N-1" calibration results. The security of the grid in different conditions are analyzed and the solutions of improving the security of networks are proposed. In this way, the diagnosis for the distribution networks changes from qualitative indicators to quantitative ones, which is a guide to the development of the distribution networks and improvement of operation and maintenance in different regions.

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Methods

Security criterion analysis of supply

Learning from the advanced technologies and ideas of othercountries and considering the background in China, the National Energy Administration issued the power supply security standard, DT/T 256–2012, for urban networks. The reliability level of supply not only depends on the quality of components and the level of operation and maintenance but also the damage of the load after components' outage [4]. The security criterion of supply and safety standards should be set to meet the requirements of security diagnosis [5].

Power supply security standards for urban areas

The regulations are comparatively specific in the power supply security standards for urban areas in China, which chooses common load groups in distribution networks. The security level suitable for distribution networks is indicated in Table 1.

Supply security criterion analysis for urban areas

According to the network structure in China, the capacity of the common equipment is shown in Table 2 [6].

In this table, the loading rate of transformer is 50 % ~ 70 %. The capacity of the line is calculated by $S=\sqrt{3}UI$, where U is the voltage of the line, and I is the carrying capacity of the line. Considering lines can not be operated with full loading, 40 % ~ 50 % of the capacity was picked as the transmission capacity of the line.

The load groups are divided into 6 levels A to Fin terms of their sizes, based on the power supply security standards for urban networks in China [7, 8]. The higher level the load is, the shorter the restoring time is after the circuit outage, and the higher the extent of recovery is.

This paper focuses on the security diagnosis of distribution networks where the levels A to C of the load groups are selected for analysis.

A. The load group ranges between 0 and 2 MW. The typical capacity of a 10/0.4 kV transformer is from 0.015 to 1MVA. Two neighboring section switches divide several (usually less than 5) 10/0.4 kV transformers into a unit. The load of every unit is from 0 to 2MV and does not need to be supplied by the other circuits.

B. The load group varies from 2 to 12 MW. The transmission capacity of a 10 kV line is 3–4MV. The common capacity of a 35/10 kV transformer is 31.5MVA, 20MVA, 16MVA and 5MVA. The typical capacity of a 35/10 kV substation can be 5*2MVA, 16*2MVA, whose load is between 5 and 10 MW.

C. The load group ranges from 12 to 180 MW. The transmission capacity of a 35 kV line is 12–15MV. The common capacity of a 110/10 kV transformer is 63MVA, 50MVA, 40MVA, 31.5MVA and 20MVA. The typical capacity components of a 35/10 kV substation are 31.5*2MVA, 40*2MVA, 50*2MVA, 63*2MVA and 63*4MVA, whose load is between 30 and 170 MW.

The quantification of the restoration capacity is different at the different levels of the load groups [9]. The specific analysis can be stated as follows:

(1) Load groups-2 MW. 2 MW is the maximum load of a segment on a medium voltage 10 kV line. Load group-2 MW represents a load of MV line without the outage segment.

(2) Load groups-12 MW. 12 MW is a load of a 35 kV line. Load group-12 MW represents a total load of a 110/10 kV substation minus the load of a 35 kV line.

(3) Load groups-60 MW. 60 MW is a load of a 110 kV line. Load groups-60 MW represents a total load of a 220/110 kV substation minus the load of a 110 kV line.

(4) 2/3 of load groups. By analyzing the situation of China, the typical capacity, in summary, is 2/3 of the annual peak load (the typical load is the level under which the load in 80 % of evaluation time should be). So the load group of C does not lose the load in the case of the "N-1" planned outages while losing a part of the load in the case of the "N-1" failure outage. Network reconfiguration by the remote operation can regain 2/3 of load groups. After 3 h, all load groups recover.

Table 1 Security standards of supply for urban China (common load groups in distribution networks)

Supply level	Scope of load groups (MW)	"N-1" outage	"N-1-1" outage	comment
A	≤2	After maintenance: restore load groups	No requirement	
B	2 ~ 12	(1) In 3 h: load restored = load groups-2 MW (2) After maintenance: restore load groups	No requirement	
C	12 ~ 180	(1) In 15 min: load restored ≥ min (load groups-12 MW, 2/3 load groups). (2) In 3 h: restore load groups	No requirement	*[a]

*[a]: User group is generally supplied by two (or more than two) normally-closed circuits or one circuit but can be switch to other circuits by artificial or automatic switch. The load group is the maximum load of the use group
The table above shows that the "N-1" outage is the main point to be considered in distribution networks

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Table 2 Capacity of common equipment in China

Equipment	Common capacity of transformer/Limiting capacity of line (MVA/MW)	Load of transformer/transmission capacity of line (MW/MW)	Load level
10/0.4 kV Transformer	1, 0.8, 0.5, 0.4, 0.315, 0.2, 0.05	0.5	A
10 kV Line	8	3 ~ 4	B
35/10 kV Transformer	20, 16, 5	5 ~ 10	B
110/10 kV Transformer	63, 50, 40, 31.5, 20	30 ~ 170	C
35 kV Line	30	12 ~ 15	C
110 kV Line	100	40 ~ 50	C

Security diagnostic process
Security diagnostic process of supply
After analyzing the power supply security standards for urban areas in China and establishing the basis of quantitative indicators, the security diagnostic process can be established, which is shown in Fig. 1.

In this figure, based on the quantitative outcomes of the power supply security standards for urban areas in China, a "N-1" verification module was firstly used for grid analysis, and then deal with the results together with the comparison module to derive conclusions and solutions. The whole assessment process is specifically introduced as follows.

"N-1" Verification module
The inputted network structure is mainly verified with the "N-1" contingency by this module. The components that cannot pass the "N-1" verification are marked, and the load transfer schemes of components are given and the sizes of the loads are recorded if passing the verification [10]. Based on the "N-1" calibration, topology analysis, connection mode analysis, power flow calculation and transfer scheme analysis are used to verify the grids, completely and comprehensively [11, 12].

The basic data processing module consists of three parts: topology analysis, connection mode analysis and power flow calculation, which is shown in Fig. 2.

The raw data of the system is combining through, and the result is converted to be used by power flow calculation mentioned in "N-1" verification. The connection between main transformers and lines, and the information of switches' state are obtained from the topology analysis to prepare data for a set of switching operation choices in the calculation of "N-1" verification. The output power of the main transformers and the power flow through components can be obtained by the power flow calculation to prepare data for the maximum transfer load of the main transformers and
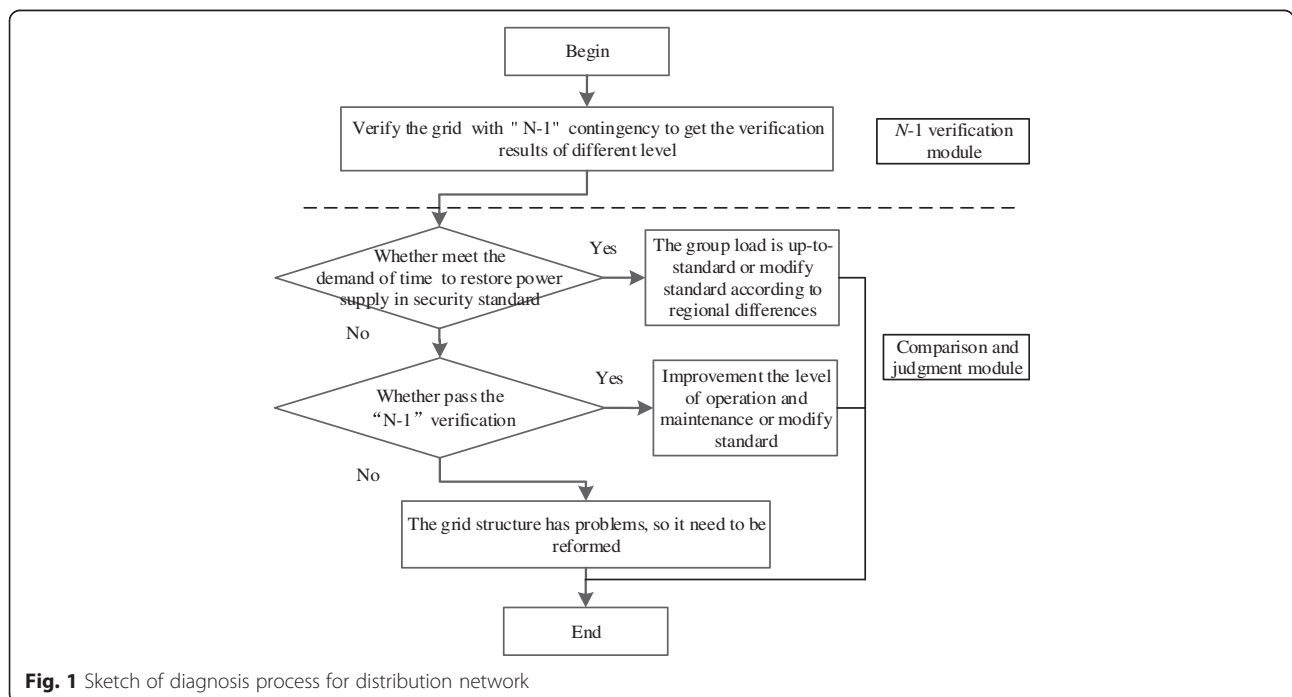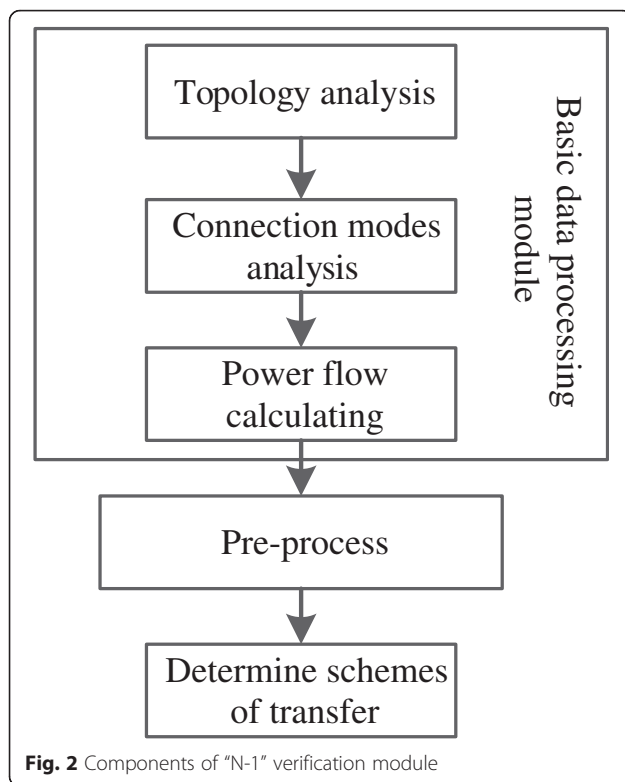

Fig. 1 Sketch of diagnosis process for distribution network

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Fig. 2 Components of "N-1" verification module

the lines. Furthermore, connection mode analysis and power flow calculation are combined to prepare for "N-1" verification.

The pre-processing has two functions: eliminating the data which cannot obviously pass the verification and put them into the result table; and selecting the data which can obviously pass the verification and put them into the result table. The rest data is put into the table of components that need to be verified.

The data that cannot obviously pass the verification includes the single radial line obtained through the topology and connection mode analysis, which has no way to be transferred. If there's a failure at outlet section of the substation bus, it will lead a wide outage in the area. So the single radial line can be directly determined.

The data that can obviously pass the verification is the situation where the main transformer with the maximum capacity in the substation has a failure and another main transformer can supply all the loads in the substation. So this situation can be directly determined.

The pre-processing effectively reduces the number of components meant to be verified, which can simplify the process and improve the speed of verification.

Determining schemes of transfer are the core parts of the "N-1" verification module. Its function is to

verify the components and record the size of the transferred load.

Comparison and judgment module

After analyzing the grid with the "N-1" verification module, the Verification Result Table can be derived, which records whether the components pass the verification, the way to transfer and the size of the transferred load. The comparison is conducted from 3 aspects: failure of the line, failure of the main transformer and the outage of the substation [13].

Furthermore, according to the size of transferred loads and the length of transferring time, comparing with the power supply security standards for urban areas in China, the analyzing results are obtained and the solutions of improving the security of networks can be proposed.

By comparing the Verification Result Table with power supply security standards for urban areas in China, following a differential and hierarchical way to check one by one, the comparison result has a high reliability. Based on this, the network structure is further analyzed.

The load groups of different levels all meet the demand in power supply security standards for urban areas in China. This kind of loads meets the details of the standard from two aspects of transferring time and the size of transferred loads. Because different regions possess differing development levels, if the practice time is usually shorter than the standard, the standard can be modified to drive the development the network structure and the level of operation and maintenance.

There are load groups of some levels do not meet the power supply security standards for urban areas in China. This kind of loads can not meet the details of standard from two aspects that load can't be transferred or transferred load don't meet load capacity required [14]. The Result Table of "N-1" verification is checked to get the information whether the components pass the verification.

(1) If the component can pass the verification, the reason of being substandard is that the time of manual reconstructing is too long when the load is transferred, so the level of operation and maintenance should be improved [15, 16]. At the same time, the practical situation of the region should be considered. If they can't generally meet the standard, the standard needs to be modified to fit the region.

(2) If only a part of the component cannot pass the verification, the reason of being substandard is structure of power network, so the network should be reformed [17]. How to reform the network is a difficult issue which is not discussed in this paper.

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Results and discussion

Combined with the diagnostic method for the distribution networks based on power supply safety standards, a case study is conducted to verify the correctness of the proposed method.

Diagnosis of region-A

According to the diagnostic method and process above, the region-A is analysed as a case to verify the feasibility of this method. And the practical case of the structural parameters and the analysis results are displayed as follows.

There are three substations in the region-A, whose diagram is shown in Fig. 3. Station A1 is a 110 kV substation located in the northwest, and the power supplies a part of the industrial applications at the north of Road and a few residential applications. Currently, there are 26 lines in the coverage of this regional power supply. Station A2 is a 35 kV substation in the southwest, which mainly supplies for the western residential applications. Correspondingly, there are 16 lines. And the 35 KV station A3 located in the mid-east like A2, mainly supplies for the western residential applications, but it has 14 lines. The A2 and A3 cannot be interconnected because of the natural barrier.

The time standards of the operation and maintenance level are: 10 h for breakdown maintenance; 5 h for manual reconstruction; 20 min for remote control reconstruction and 60 s for automatic switching.

"N-1" Calibration results of region-A

According to the above method, region-A is verified with "N-1" calibration, which includes the main transformers and lines.
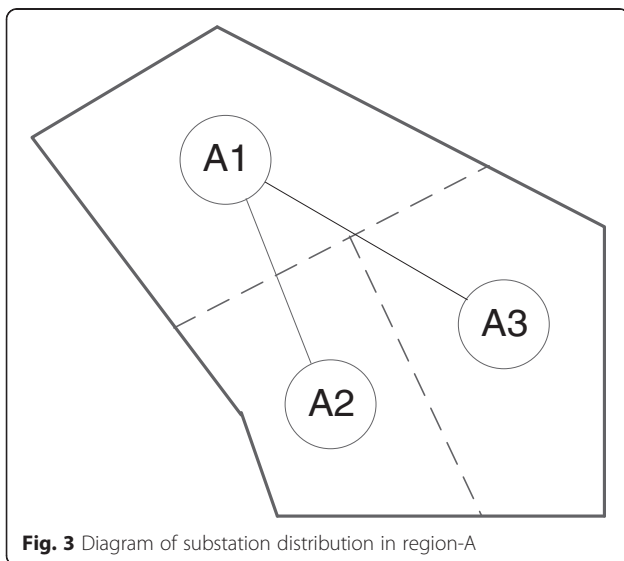

Fig. 3 Diagram of substation distribution in region-A

According to the diagnostic process, the "N-1" calibration results of the lines and main transformers are obtained, as indicated in Tables 3 and 4.

Comparative analysis results of region-A

When there is a fault at the line, it is divided into two parts, which are the faulty section and non-faulty section. For the faulty section, the power is restored after maintenance tasks, so it is necessary to ensure that whether maintenance time could meet the safety standard requirements. For the non-faulty section, the transferring time is checked because its load can be transferred by the link line. The following analysis assumes that the automation level of region-A is relatively low, and the transferring is based on the manual switching operation.

According to the analysis results above, the detailed descriptions are stated as follows.

(1) Line 5, 6, 7, 8 in Station A1, Line 39, 40, 41, 42 in Station A2, and Line 51, 52, 53, 54, 55, 56 in Station A3. These single-radiation lines cannot pass the "N-1" calibration. When there are faults, the loads cannot be transferred, so the power supply for the non-faulty section comes after maintenance. The load class of some lines (Line 5, 6, 8, 39, 40, 41, 42, 51, 52, 53, 55 and 56) can be expressed as A, and the maintenance time of them is 10 h, which cannot meet the safety standard requirements. Besides, carrying the large load, Line 7 in Station A1 and Line 54 in Station A3 can be expressed as B and cannot transfer all of load required when faults happen, so they must be upgraded to transfer load and their transferring time should meet the safety standard requirements.

(2) Line 10 in Station A1 and Line 45 in Station A3. These lines with single tie cannot satisfy the "N-1" calibration owing to the lack of transferring capacity. For the non-faulty section, either 5 h for transferring or 10 h for maintaining to restore the power supply cannot meet the safety standard requirements.

(3) Remain lines. They have ties and could pass "N-1" calibration. But similarly, 5 h for transferring to restore the power supply would not meet the safety standard requirements.

According to the analysis above, the operation and maintenance level of this region cannot satisfy the safety standard requirements; especially, there are two lines (Line 7, 54) which need to be improved, so the operation and maintenance level of this region should be upgraded.

When there are faults in the main transformers, internal transferring of station should be considered firstly. It can be completed automatically, and the time is about 60 s. If the loading rates of main transformers are high,

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Table 3 "N-1" calibration results of 10 kV lines in region-A

Substation	Line name	Connection type	Line load (kW)	Translational load (kW)	Whether pass	Substation	Line name	Connection type	Line load (kW)	Translational load (kW)	Whether pass
A1	Line 1	Single-tie	1524	2476	Yes	A2	Line 29	Multi-tie	1120	2880	Yes
A1	Line 2	Multi- tie	1653	1347	Yes	A2	Line 30	Multi-tie	1333	2267	Yes
A1	Line 3	Multi-tie	2387	1613	Yes	A2	Line 31	Multi-tie	1519	2481	Yes
A1	Line 4	Single-tie	1559	2441	Yes	A2	Line 32	Multi-tie	1021	1979	Yes
A1	Line 5	Single-radiation	1346	–	No	A2	Line 33	Single-tie	1105	2895	Yes
A1	Line 6	Single-radiation	1847	–	No	A2	Line 34	Single-tie	1231	2469	Yes
A1	Line 7	Single-radiation	2044	–	No	A2	Line 35	Single-tie	1152	2648	Yes
A1	Line 8	Single-radiation	1523	–	No	A2	Line 36	Single-tie	1226	2774	Yes
A1	Line 9	Multi-tie	2102	1860	Yes	A2	Line 37	Multi-tie	1237	2763	Yes
A1	Line 10	Single-tie	1879	2121	No	A2	Line 38	Single-tie	1032	2868	Yes
A1	Line 11	Multi-tie	1865	2135	Yes	A2	Line 39	Single-radiation	1255	–	No
A1	Line 12	Multi-tie	1623	2377	Yes	A2	Line 40	Single-radiation	1065	–	No
A1	Line 13	Multi-tie	1116	2884	Yes	A2	Line 41	Single-radiation	1126	–	No
A1	Line 14	Multi-tie	1356	2644	Yes	A2	Line 42	Single-radiation	1176	–	No
A1	Line 15	Multi-tie	1645	2355	Yes	A3	Line 43	Multi-tie	1744	2256	Yes
A1	Line 16	Multi-tie	2496	1504	Yes	A3	Line 44	Multi-tie	1206	2794	Yes
A1	Line 17	Multi-tie	1212	2788	Yes	A3	Line 45	Multi-tie	2343	1857	No
A1	Line 18	Single-tie	1742	2258	Yes	A3	Line 46	Multi-tie	1542	2258	Yes
A1	Line 19	Single-tie	1435	2565	Yes	A3	Line 47	Single-tie	1615	2385	Yes
A1	Line 20	Single-tie	1318	2682	Yes	A3	Line 48	Multi-tie	1375	2625	Yes
A1	Line 21	Multi-tie	1764	2236	Yes	A3	Line 49	Single-tie	1464	2536	Yes
A1	Line 22	Single-tie	2317	1683	Yes	A3	Line 50	Single-tie	1717	2283	Yes
A1	Line 23	Single-tie	1435	2565	Yes	A3	Line 51	Single-radiation	1032	–	No
A1	Line 24	Single-tie	1767	1206	Yes	A3	Line 52	Single-radiation	1390	–	No
A1	Line 25	Single-tie	1232	2768	Yes	A3	Line 53	Single-radiation	1258	–	No
A1	Line 26	Single-tie	2315	1685	Yes	A3	Line 54	Single-radiation	1015	–	No
A2	Line 27	Single-tie	1235	2565	Yes	A3	Line 55	Single-radiation	1265	–	No
A2	Line 28	Single-tie	1167	1206	Yes	A3	Line 56	Single-radiation	1034	–	No

internal transferring of station would not supply the power to all lines, so the excess lines would be cut. And then connections between stations should be taking into account. If there is a sufficient connection capacity between stations, the load will be transferred by other stations. Accordingly, whether the transferring time reaches the safety standard requirements can be confirmed. The rest part, which cannot be transferred, gets power supply after maintenance. The results after failure of transformers are shown as Table 5.

According to the power supply safety standards, it requests 8 h for breakdown maintenance, 3 h form anual reconstruction to restore the power supply and 60 s for automatic switching.

Table 4 "N-1" calibration results of main transformers in region-A

Region	Substation	Load (MW)	Main transformer capacity (MVA)	Total capacity of 10KV Part (MVA)	Translational load of link line (MVA)	Translational Load of main trans (MVA)	Whether pass	Loss load
A	A1	41.3	2×40	80	5.7	40	No	1.3
	A2	23	2×20	40	5.7	20	No	3
	A3	21	2×20	40	0	20	No	1

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Table 5 Failure analyses results of transformers in region-A

Region	Substation name	Load (MW)	Main transformer Capacity (MVA)	Total capacity (MVA)	Translational load of main trans (MW)	Recovery time	Translational load of lines (MW)	Recovery time	Loss load (MW)	Recovery time
A	A1	41.3	2 × 40	80	40	60 s	1.3	5	0	–
	A2	19	2 × 20	40	19	60 s	3	5	0	–
	A3	20	2 × 20	40	20	60 s	0	–	1	10

According to the analysis results above, the detailed descriptions are shown as follows.

(1) Substation A1: Assuming that each main transformer could carry 130 % of the load when faults happen in another transformer, then the total load of the faulty transformer would be transferred through automatic internal transferring of station in 60 s, which reaches the safety standard requirements. Assuming that each main transformer could carry 100 % of the load, and the automatic switching could make a part of loads transferred, the remaining part would be transferred through the connection between stations, therefore there will be 1.3 MW load transferred in 5 h, which cannot reach the safety standard in view of the overlong time.

(2) Substation A2: Assuming that each main transformer could carry 130 % of the load when faults happen in another transformer, then the total load of the faulty transformer would be transferred through automatic internal transferring of station in 60 s, which reaches the safety standard requirements. Assuming that each one could carry 100 % of the load, and the automatic switching could make a part of loads transferred, the remain part would be transferred through the connection between stations, therefore there will be a 3 MW load transferred in 5 h, which cannot reach the safety standard requirements in view of the overlong time.

(3) Substation A3: Assuming that each main transformer could carry 130 % of the load when faults happen in another transformer, then the total load of the faulty transformer would be transferred through automatic transferring in station in 60 s, which reaches the safety standard requirements. Assuming that each one could carry 100 % of the load, and the automatic switching could make a part of loads transferred, different from the above, the remaining part would not be transferred due to the lack of connection between stations; therefore the 1 MW load would get power supply only after the 10 h maintenance, which cannot reach the safety standard requirements.

Summary of analysis results

A2 and A3 cannot be interconnected because of the natural barrier, so the connection condition of the whole region is poor. Carrying a large load, defined as Class B, Line 7 in Station A1 and Line 54 in Station A3 cannot transfer loads to reach the standard when there is a failure. Obviously, it is necessary to upgrade these lines. Besides, a lot of single-radiation lines urge the region to improve the structure of the network. The low operation and maintenance level also makes region A cannot reach the power supply safety standard. However, it is more appropriate to revise this standard to avoid the negative impact of the strict rules on regional development. Therefore, in order to adapt to the actual situation and promote the level of operation and maintenance, 9 h for breakdown maintenance and 4 h form anual reconstruction are set up.

Conclusions

As the power supply safety standards need to be improved, the diagnostic method using the reliability index cannot offer the quantitative analysis of the power grid structure. The diagnostic method for distribution networks based on power supply safety standards has the following characteristics:

(1) The power supply safety standard has profound theoretical basis, a practical background and strict logic. It is a complete quantitative criterion, which is simple, clear and easy to use. According to the actual situation of Chinese urban power grids, it can fully reflect the structure performance level of Chinese power grid currently, based on practical experience in many years and the results of the survey.

(2) The diagnostic method has a distinct and strong structure. The standards considering the actual situation are not only distinguished from different levels of loads, but also from the grid structure level.

(3) In view of the different levels of structure, it is significant to make a quantitative index distinguishing the difference, so this standard has a great guiding significance for the diagnosis of the distribution networks.

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To summarize, this standard can be used to give appropriate solutions of improving the security of networks and revise the safety standard on the basis of the regional characteristics.

Authors' contributions

JH and SG proposed the diagnostic process of the distribution network. JH, HL, XZ, and HL carried out the theoretical studies and drafted the manuscript. BW and ZC performed the case study. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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