Urban Distribution Network Operation Risk Index System and Calculation Method

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Abstract. A reasonable index system is an important basis for risk assessment. Firstly, aiming at the shortcomings of the existing index system establishment and evaluation methods, combined with the structural and operational characteristics of urban distribution network, a risk index hierarchy including load loss, grid structure integrity, equipment loss and grid security margin is proposed based on the construction principle. Then, the calculation methods for the consequences of each risk index are given from the perspective of facilitating engineering application. Finally, the application example of power grid in a city is given.

1. Preface

The main purpose of the grid operation risk assessment is to identify and monitor the possible risk scenarios, and measure the possibility and occurrence of the grid comprehensively [1]. The grid risk level and weak links for the dispatching operators can be timely grasped, and risk management measures to make decision can be developed with the consequence of risk assessment.

The operational risk assessment index system is the key to the risk assessment of urban distribution network. At present, there are some related researches on risk assessment index system at home and abroad. The literatures [2-4] put forward the power grid risk index and voltage collapse risk index; [5] proposed risk index such as overload, low voltage, voltage collapse and power angle instability; [6] proposed the failure load, overload and voltage over-limit risk from the perspective of power supply safety of distribution network, and the overall risk level of the system is determined by analytic hierarchy process (AHP); [7] uses the load loss to characterize the risk consequences; [8-10] give the definition and calculation method of the risk index from the aspects of the reduction of supply load. In addition, many power supply companies have explored and practiced the design, development and application of risk assessment system, such as East China Power Grid[11], Jinhua[12], Ningbo[13], Hunan[14-15] and Chongqing[16] companies, etc., and have established corresponding operational risk index system and calculation specifications combined with engineering applications in recent years.

At present, the main problem in the study of urban distribution network operation risk index is that the existing index systems are mostly aimed at the construction of transmission networks, including static security and transient security of the power grid. On the one hand, the transient safety index mentioned cannot reflect the accidents objectively. On the other hand, for urban distribution networks, the problem of power angle and frequency stability is not prominent, and the availability of transient
safety index is not high. The existing urban distribution network safety risk index mainly use the severity function [2]. To calculate the risk consequences, for example, the literature [10, 15] constructed index such as equipment overload, section overload, voltage over-limit, frequency deviation, etc., which are convenient for accumulating combinations to form overall risks, but it is difficult to comprehensively and objectively reflect the consequences and actual loss of grid faults, the accuracy and comprehensiveness of the index need to be improved.

On this basis, According to the structure and operation characteristics of the urban distribution network, this paper addresses the shortcomings of the existing index system and the evaluation method, considers the problems of urban distribution network structure, grid safety margin, loss of load and economy fully, and proposes a set of practical urban grid operation risk index system combined with the related regulations, in which the calculation method of each risk index is given.

2. Principles for the construction of risk index system

2.1 Principles for screening and constructing basic index
Grasp the structural characteristics and operational characteristics of the urban distribution network; follow the relevant regulations, regulations and technical guidelines and other normative documents.

On the one hand, the Regulations on Emergency Response and Investigation and Handling of Electric Power Accidents[17] and the Regulations on the Investigation of Safety Accidents of State Grid Corporation (hereinafter referred to as “Investigation Procedures”) [18], etc., have regulated the classification criteria of power accidents (incidents), according to the classification criteria, the relevant operational risk index can be constructed; on the other hand, the risk norms such as “Technical Specifications for Quantitative Evaluation of Operational Risks of China Southern Power Grid” [19] and “Criteria for Risk Management and Control of Chongqing Power Grid” [16] have developed and deepened the risk assessment work, and have made many practical explorations on risk assessment. The above-mentioned power enterprise specification documents which are tested through several years provide a reference basis for the technical basis and practical application of the power grid risk assessment. Effectiveness and practicality of index system can be ensured through screening and constructing the basic index based on the above-mentioned procedures and normative documents.

2.2 Construction principle of index system
Based on the selected basic index, the index system reveals the overall status of the grid operation by analyzing, researching and mining the information reflected by the basic index. In order to ensure the rationality and accuracy of the urban distribution network operation risk assessment, the construction of the index system should meet the following principles. Hierarchy: the entire index system should have a sense of hierarchy, overall index and first-level index, first-level index and second-level index; Integrity: the index system should cover all aspects of different levels and different angles of urban distribution networks demand, and index setting is neither repeated nor missing; Practicality: the index system should be easy for the dispatching operators to understand and use, and the operability is good and easy to implement.

3. Risk index system
Risk index include both scenario probability and scenario consequences. The consequences of the risk scenario are the hazards caused by grid faults, which are divided into direct and indirect consequences. The direct equipment loss refers to the economic loss of the faulty component after the equipment fails. In terms of indirect consequences, after the fault occurs, the node may be isolated, the system parameters may be over limited, and the grid load may be reduced. First, to identify the difference in power supply reliability of different types of loads, three types of load loss index are established. Second, to evaluate the structural integrity under the same load reduction after the grid fault, substation voltage loss, power plant stop and grid disconnection reduce the strength of the grid and the reliability of power supply. Power grids are normal in most of the N-1 conditions, but some equipment parame-
ters are closed to the limit operation, so that the system's anti-n-2 fault ability is reduced. To characterize the indirect consequences caused by such faults, the grid N-1 safety margin index is establish.

Therefore, this paper constructs the index system shown in Figure 1. The index system includes four first-level index, such as equipment direct loss risk, grid structural integrity failure risk, N-1 grid safety margin risk and grid load loss risk, which are further divided into first-level index to form multiple sub-items index.

![Urban distribution network risk index system](image)

**Figure. 1. Urban distribution network risk index system.**

4. Risk consequence calculation method

4.1 N-1 grid safety margin

The grid safety margin refers to the distance from the normal operating state of the grid to the critical safe operating state. When the urban distribution network fails, due to the section and equipment overload, the node voltage is close to the limit operation, the grid safety margin is reduced, and the risk of power outage is increased. Therefore, the N-1 grid safety margin is proposed, including static voltage safety margin, line current margin, section current margin and transformer load margin.

\[
K_{vi} = \frac{V_{0i} - V_{ni}}{V_{vli} - V_{ni}} \quad (V_{0i} < V_{ni}) \\
K_{chi} = \frac{V_{0i} - V_{ni}}{V_{vhi} - V_{ni}} \quad (V_{0i} > V_{ni}) \\
K_{li} = \frac{I_{0i}}{I_{mi}} \\
K_{li} = \frac{S_{li}}{S_{Ni}} \\
K_{Mi} = \frac{P_{0i}}{P_{maxi}}
\]

Where: \( V_{0i} \) is the current voltage of the bus node \( i \), which is obtained by the power flow calculation in the risk scene; \( V_{vli} \) is the low voltage limit value of the node \( i \); \( V_{vhi} \) is the high voltage limit value of the node \( i \); \( V_{ni} \) is the rated voltage of node \( i \); \( I_{0i} \) is the current limit of line \( i \); \( I_{mi} \) is the current of line \( i \); \( S_{li} \) is the rated capacity of transformer \( i \); \( S_{Ni} \) is the current apparent power of transformer \( i \); \( P_{0i} \) is the current power of section \( i \); \( P_{maxi} \) is the grid operation control section limit of section \( i \).
Due to the wide geographical range, the large voltage level span, the large number of nodes, branches and sections of urban distribution network, the dispatching operation personnel mainly pay attention to the voltage monitoring control points, key sections and important equipments of the power grid when analyzing the voltage and branch current conditions. The grid safety margin index mainly calculates the static voltage safety margin of the grid voltage monitoring control points, the current-carrying margin of important equipments, and the tidal margin of the critical sections. Meanwhile, due to the different voltage levels, areas and functional uses of various power equipments in the power grid, the equipment importance correction factor is introduced, and each index is weighted and modified to characterize the different severity of the same safety margin of different voltage levels.

The margin index reflects the distance between the parameters of the grid voltage, the branch current, and the limits. The above margin index calculates the margin value of a certain node, a branch or a section, and the value of each item of the margin index obtained by each margin value needs to adopt a reasonable method. This paper comprehensively considers the maximum and average values of each margin value, which reflects the unsafe "wooden barrel effect" and "overall effect" of the grid, that is, grasping the main contradictions while also taking into account the overall level of the grid, the expression is as follows:

\[ R = \omega_1 \times \max(\alpha_i R_i) + \omega_2 \times \text{ave}(\alpha_i R_i) \]  

Where: \( R \) is the itemized margin index (voltage safety margin, line current margin, transformer load margin and section tidal margin); \( i=1, 2, ..., n \) are number of lines, transformers or sections; \( R_i \) is the margin value; \( \alpha_i \) is the node, line, transformer or section importance correction factor; \( \omega_1 \) and \( \omega_2 \) are the weight coefficient, and \( \omega_1 + \omega_2 = 1 \).

4.2 N-1 grid safety margin
The network structure of the urban distribution network coexists with the ring network and the radiant network. When the power grid is seriously faulty, it may cause the loss of voltage or the power plant to stop completely. Therefore, the failure of the structural integrity of the power grid is characterized in terms of grid disconnection, substation voltage loss, and power plant shutdown.

(1) Grid disconnection: when a serious fault in the grid causes the grid to be disengaged, the power system will remove a large amount of load and generators, and the system will no longer be interconnected.

(2) Substation failure loss: it means that the bus voltage at all levels of the substation (excluding station power) has dropped to zero. The topological analysis of the risk scene is carried out to obtain the non-generator nodes whose voltage drops to zero.

(3) Power plant stop: refers to a power plant whose external active load reduced to zero (although the load transferred by the power grid through the power bus is not stopped, it is still regarded as “the whole plant is out of power”). Firstly, through the topological analysis of the risk scene, the generator nodes from the running state to the non-operating state are obtained. Secondly, if the grid has a limit condition, it is also necessary to calculate the generator node in the load reduction system where the external active load drops to zero.

4.3 Grid load loss
When the system fails, the branch current and the node voltage exceeds the limit, the current risk assessment is described by a custom severity function. In this paper, the load reduction is used to replace the grid parameter over-limit severity to quantify the consequences of the risk scenario accurately. At the same time, considering power supply reliability of important users and the impact of power loss, three types of load loss are proposed. The type \( i \) load loss at the grid node \( j \) can be calculated by the following formula:

\[ X_{ij} = L_{ij} + S_{ij} \]  

Where, \( L_{ij} \) is the load loss of the \( i \)-th type load at the node \( j \) after the faulty component is out of operation, which can be calculated by the topology analysis. \( S_{ij} \) is the load loss of the \( i \)-th class at the node \( j \) to meet the safe operation condition, which can be calculated by the load reduction model.
The load reduction obtained by equation (7) cannot correspond to the "Investigation Procedures". On the one hand, the “Investigation Procedures” assesses the total number of loss load caused by faults when assessing accidents (incidents), without distinguishing the types of loads. On the other hand, the “number of households” is a post-accident analysis index in the power outages which is not applicable to the expected failure analysis. In order to reflect the power supply reliability of important users and the impact to important users of power loss, this paper assigns weight to the loss of three types of load, and the load loss after total weighting is obtained from the grid load loss index value. Grading is as follows:

\[ W = \omega_1 \sum_j X_{1j} + \omega_2 \sum_j X_{2j} + \omega_3 \sum_j X_{3j} \]  

(8)

Where: \( X_{1j}, X_{2j}, X_{3j} \) are the load reduction of three types of node \( j \); \( \omega_1, \omega_2, \omega_3 \) are the importance correction factor of three types of load.

4.4 Equipment direct loss

When the equipments (transformers, transmission lines, circuit breakers) failure occurs, the faulty equipment itself suffers certain damage, which is called equipment direct loss, which is divided into direct loss of circuit breaker, transformer, and transmission line.

5. Case study

Take a city power grid as an example. Assume that the load ratios of the load nodes of the system are 0.1, 0.2, and 0.7, respectively. The load importance is taken as 2.0, 1.5, and 1.0 according to the literature. The direct cost of setting up the system for power transmission and transformation equipment: the direct cost of transformer troubleshooting is 500,000 yuan/time; the direct cost of troubleshooting for transmission lines is 120,000 yuan/time; the direct cost of circuit breaker troubleshooting is 70,000 yuan/time. The expected fault scenario is 220kV Beijia line A and B double-circuit line on the same tower. As shown in Figure 2, the probability of failure [10] is 6.67E-5, ignoring the malfunction and refusal of the circuit breaker.

**Figure 2.** Tripping of Double Circuit Line on the Same Tower of 220 kV Beijia A-B Line.

According to the risk index consequence calculation method provided in this paper, the consequence value of each index is obtained. Combined with relevant regulations, specifications and standards, the calculation results and grading results are shown in Table 1.

**Table 1.** Index Consequence Value in the Fault Scenario.

| Primary index                  | Sub-index    | Consequence value calculation | Consequence rating |
|-------------------------------|--------------|-------------------------------|-------------------|
| N-1 grid safety margin        |              |                               |                   |
| Power grid structural in-     | Grid dis-    |                               |                   |

5
Substation integrity failure

| Substation voltage loss | There are 2 220kV stations, 7 110kV stations and 2 110kV subscriber stations. | Level 5 |

| Power plant stop | — | — |

| Grid load loss | First type of load loss: 52MW, the second type of load loss is 104MW, the third type of load loss is 364MW, and the loss of load is: $52 \times 2 + 104 \times 1.5 + 364 = 624$MW | Level 5 |

| Second type load loss | — | — |

| Third type of load loss | A and B: $12 \times 2 = 240,000$ Yuan. | Level 2 |

From the results of Table 1, the failure consequences are mainly manifested in substation voltage loss, grid load loss and equipment direct loss. The fault in this grid is serious shown by the index, mainly because voltage level of 220kV Beijia A and B lines is high, and the load is large. When the double-circuit lines are tripped, the load cannot be completely transferred to other lines, which causes a large load reduction and power loss of the substation.

Table 1 calculates the consequences and grading results of each index. To illustrate the application of the risk index consequence calculation method, the risk level of the fault is determined by combining the probability of failure. It is assumed that the failure probability level is 4th where the failure probability is $1E-6-5E-4$. This paper assigns weights to each consequence. The weights of the first-level index are 0.05, 0.55, 0.35, and 0.05, and the fault consequence level is 4.6. The risk level is obtained based on the probability level of the failure and the level of the consequences:

$$L = \text{round}((1 - \mu)L_p + \mu L_s)$$

Where $L_p$ is the probability level; $L_s$ is the consequence level; $\mu$ is the weighting factor, here is set to 0.6, $\text{round}(\cdot)$ is rounded off, the lowest risk level is level 1, and the highest risk level is level 9. It is calculated that $L=\text{round}(0.4\times4+0.6\times4.6)=4$, and the comprehensive evaluation result shows that the risk level of the fault scenario is 4, which is medium risk. The fault risk level information is easy for the dispatching operation personnel to understand. After the fault risk level is clarified, corresponding preventive control can be performed to reduce the risk level.

6. Conclusion

The urban distribution network operation risk index system is proposed in this paper, which can comprehensively reflect the risk factors and consequences of urban distribution network operation. And the calculation methods of each sub-index and the fusion method of the first-level index to calculate the risk level of each fault scenario are given. It is conducive for dispatching operators to grasp the risk level and weak links of the power grid in a timely manner, and reasonably formulate risk management and control measures to provide decision support.

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