The Reliability Evaluation of Power Supply Distribution System Based on Distribution Automation

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Abstract. This paper presents an improved failure mode and effect analysis for reliability evaluation of distribution network. By introducing the state factor of switch automation, the calculation formula of power supply reliability index of load point is modified, and the traditional consequence analysis method of fault mode is improved. Taking the test model of overhead lines as an example, the effectiveness of the improved method is verified, and the importance of distribution automation in the reliability improvement of distribution network power supply is affirmed, and the practical principle of terminal configuration is given in conjunction with the situation of distribution network in Anhui Province.

1. Introduction

In February 2019, State Grid Corporation of China proposed the strategic goal of “two-network convergence”. This paper intends to actively promote the construction of smart grid through distribution terminal automation. The distribution network is directly connected to the user, and the reliability of the power supply has an extremely important impact on the power users. Therefore, it is of great significance to strengthen the reliability assessment of the distribution network[1]. Distribution automation[2] can achieve rapid location and isolation of power grid faults, thus quickly recovering power supply, which is an important means to improve the power supply quality of the distribution network and improve the reliability of power supply[3-6].

At present, there are many calculation methods for the reliability of distribution systems, such as failure mode and effect analysis method[7-9], Monte Carlo simulation method[10-12], state space method[13], network equivalent method[14], system state enumeration method, etc. The failure mode and effect analysis is based on the relationship of component combination, grid structure and operation characteristics[15], and has strong adaptability to analyze the reliability of different wiring modes. However, the time of power failure due to the failure in the method does not change with the number and location of the distribution automation terminal configuration, and is not suitable for the evaluation for the implemented automation circuit.

Based on the existing failure mode and effect analysis, this paper introduces the switch automation state factor, and combines the switch state information reported by the automation terminal to determine the action switch position. The fault finding time and the switching action time are obtained according to the power distribution automation state of the action switch. The reliability evaluation index obtained by the improved failure mode and effect analysis can fully reflect the effect of implementing distribution automation on improving the reliability of the distribution network. The availability and effectiveness of the improved method are verified by an overhead multi-segment single contact test model in a city's Class A power supply area. Finally, combined with the actual situation of distribution network in Anhui
area, considering the impact of different terminal configuration schemes on reliability and economy, the practical principle of terminal configuration is given.

2. Reliability evaluation index of the distribution system
The reliability of the distribution system is used to quantitatively evaluate the reliability of the distribution system. Currently, there are several typical reliability indicators.

1) SAIFI (System Average Interruption Frequency Index)
SAIFI refers to the average number of power outages of users running in the system during one year. The calculation formula is:

$$SAIFI = \frac{\text{total interruption times of customer due to failure in system}}{\text{total customers in system}} = \sum \frac{\lambda_i N_i}{N_i}$$ (1)

2) SAIDI (System Average Interruption Duration Index)
SAIDI is the average power outage duration experienced by users running in the system during one year. The calculation formula is:

$$SAIDI = \frac{\text{total interruption hours of customer due to failure in system}}{\text{total customers in system}} = \sum \frac{U_i N_i}{N_i}$$ (2)

3) CAIDI (Customer Average Interruption Duration Index)
CAIDI refers to the duration of each user that is affected by power outage in a year, and the formula is:

$$CAIDI = \frac{\text{total interruption hours of customer due to failure in system}}{\text{total interruption times of customer due to failure in system}} = \sum \frac{U_i N_i}{\lambda_i N_i}$$ (3)

4) ASAI (Average Service Availability Index)
ASAI is the ratio of the number of hours available to users in a year to the total number of hours of power required by the user. The calculation formula is:

$$ASAI = \frac{\text{total power supply time of customer}}{\text{total power supply time required by customer}} = \sum \frac{N_i \times 8760 - U_i N_i}{N_i \times 8760}$$ (4)

In the formula of (1)-(4): \( \lambda_i \) is the annual failure rate of load point \( i \); \( N_i \) is the number of users; \( U_i \) is the annual power interruption time of load point \( i \).

3. Advantages and disadvantages of failure mode and effect analysis
The failure mode and effect analysis first lists all the possible states of the system, taking the segment as the minimum unit of load transfer, analyzing each basic component and its consequences for basic failure event; then, setting the failure rate and power failure time of components under the fault condition in turn, calculate the power supply reliability index under the current fault respectively, and add the results to obtain the power supply reliability index of each load point; Finally, calculate the power supply reliability index of the entire power distribution system according to equations (1) to (4).

The failure mode and effect analysis takes the component as the smallest unit and utilizes the bottom-up analysis method, which has the advantages of simple operation and strong adaptability. However, in this method, the failure interruption times of component is a fixed value, and does not change with the installation position and quantity of the distribution automation terminal. The installed automation terminal feeds back the collected switch status of current value, voltage value and other information of component to the distribution automation master station system. The staff judges the line fault type and the fault affected zone according to the feedback data, and takes corresponding measures to isolate the fault. The power supply of the non-faulty section is restored, the faulty section is repaired, and the power supply is restored, and finally the failure interruption time of component becomes a variable. The installation of the distribution automation terminal makes the distribution network line more intelligent and visual, and the original the failure mode and effect analysis does not reflect the advantages of distribution network automation in improving the reliability of power supply.
4. Improved failure mode and effect analysis

In view of the shortcomings of the existing failure mode and effect analysis in calculating the component fault finding time and switching action time, this paper introduces the switch automation state factor, which makes it suitable for the power supply reliability evaluation of the installation distribution automation terminal line.

The fault finding time is equal to the product of the unit line fault finding time and the length of the found line. The formula is as follows:

$$t_{ij} = t_a \times l_{ij}$$  \hspace{1cm} (5)

In the formula:  $t_{ij}$ is the fault finding time of the load point $i$ under the fault $j$;  $t_a$ is the average unit line fault finding time;  $l_{ij}$ is the fault finding length of the load point $i$ under the fault $j$. The fault finding starts from the beginning of the line. If the automatic terminal is installed in the sectional switch at both ends of the fault point, the fault segment can be quickly located, and the fault finding length $l_{ij}$ is 0; if some automatic segmentation switches are installed in the line, then the fault finding length $l_{ij}$ is equal to the length of the line head end or the previous automation terminal to the fault end.

The fault isolation time is calculated as follows:

$$t_{ij2} = t_o + l_{ij2}$$  \hspace{1cm} (6)

In the formula:  $t_{ij2}$ is the fault isolation time of load point $i$ under fault $j$;  $t_o$ is the switch or circuit breaker open time;  $t_c$ is the switch or circuit breaker closing time. The on/off time of a switch or circuit breaker is determined by its degree of automation, as follows:

$$t_o = \begin{cases} 0.03h & \text{Non action type monitoring switch or circuit breaker} \\ 0.01h & \text{action type monitoring switch or circuit breaker} \end{cases}$$  \hspace{1cm} (7)

$$t_c = \begin{cases} 0.03h & \text{Non action type monitoring switch or circuit breaker} \\ 0.01h & \text{action type monitoring switch or circuit breaker} \end{cases}$$  \hspace{1cm} (8)

The repair time of fault $t_{ij3}$ is the fault repair time of the load point $i$ under fault $j$, and is the average value of the fault repair time statistics value of the fault occurrence area.

On this basis, according to whether the load point $i$ is located in the fault area, the failure interruption time $t_{ij}$ is obtained; the calculation formula is:

$$t_{ij} = \begin{cases} t_{ij1} & \text{load point } i \text{ is located in the non-fault interval} \\ t_{ij2} & \text{load point } i \text{ is located in the fault interval} \end{cases}$$  \hspace{1cm} (9)

The annual failure rate of load point $i$ is:

$$\lambda_i = \sum_{j=1}^{K} \lambda_j$$  \hspace{1cm} (10)

In the formula:  $\lambda_j$ is the failure rate of fault $j$.

According to the failure interruption time and failure rate of the load point $i$, the annual failure interruption time $U_i$ of the load point $i$ can be obtained:

$$U_i = \sum_{j=1}^{K} (t_{ij} \lambda_j)$$  \hspace{1cm} (11)

According to the above formula, the calculation formulas of the four indicators of SAIFI, SAIDI, CAIDI, and ASAII are sorted out to obtain:

$$SAIFI = \frac{\sum_{i=1}^{K} N_i \sum_{j=1}^{K} \lambda_j}{\sum_{i=1}^{K} N_i}$$  \hspace{1cm} (12)
\[ SAI_{DI} = \frac{\sum_{i=1}^{K} N_i \sum_{j=1}^{K} (t_{ij} \lambda_j)}{\sum_{i=1}^{K} N_i} \] (13)

\[ CAI_{DI} = \frac{\sum_{i=1}^{K} N_i \sum_{j=1}^{K} (t_{ij} \lambda_j)}{\sum_{i=1}^{K} N_i \sum \lambda_j} \] (14)

\[ ASAI = \frac{\sum_{i=1}^{K} N_i \times 8760 - \sum_{i=1}^{K} N_i \sum_{j=1}^{K} (t_{ij} \lambda_j)}{\sum_{i=1}^{K} N_i \times 8760} \] (15)

5. Case analysis and application

5.1 Case analysis

Figure 1 is a test model of an overhead line in a Class A power supply area of a city. The circuit length is 3km. The grid structure is a three-segment single contact, including 4 loads, each load point is 6 users, a total of 24 users, supplied by dual power. Substation outlet circuit breaker CB0 is action type monitoring terminal. Assume that the closing and opening operations of each switch are equal. The model parameters are set as follows: the failure rate of switch is 0.05, the failure rate of trunk line is 0.1/km, the failure rate of branch line is 0.1/km, the search time of per kilometer is 0.5h, the repair time of line fault is 3h, and the repair time of switch fault is 1.2h.

Taking load point LD1 as an example, when all action type monitoring terminal configurations are configured, a failure mode consequence analysis table is established, as shown in Table 1.

**Table 1.** Failure mode and consequence analysis table of load points LD1 in all action type monitoring terminals

| Fault component | Failure rate | Finding time | On/off time of each kilometer/h | Length/km | Closing time of CB0 or CB1/h | Repair time/h | Failure interruption Duration/h | Total interruption hours/h |
|-----------------|-------------|--------------|-------------------------------|-----------|----------------------------|--------------|-------------------------------|--------------------------|
| Bus             | 10          | 0.05         | 0.5                           | 0.5       | 0.01                       | 0            | 0.02                          | 0.001                    |
| Trunk line      | 11          | 0.05         | 0.5                           | 0.5       | 0                          | 3            | 3                             | 0.15                     |
|                 | 12          | 0.05         | 0.5                           | 1         | 0                          | 3            | 3                             | 0.15                     |
For the same reason, the reliability indicators of each load point in all action type monitoring terminals are shown in Table 2.

### Table 2. Failure mode and consequence analysis table of load points in all action type monitoring terminals

| LOAD   | Failure rate | Total power outage /h |
|--------|--------------|------------------------|
| LD1    | 0.6          | 0.574                  |
| LD2    | 0.6          | 0.574                  |
| LD3    | 0.6          | 0.574                  |
| LD4    | 0.6          | 0.574                  |

The power supply reliability index of the system is calculated from equations (12) to (15), for details see Table 3.

### Table 3. Reliability index of the full three-remote system

|       | SAIFI  | SAIDI  | CAIDI  | ASAI   |
|-------|--------|--------|--------|--------|
|       | 0.6    | 0.5740 | 0.9567 | 99.9934|

According to Table 1 to Table 3, the power supply reliability under the condition that the switch is configured with different power distribution terminals is calculated, and the system reliability index is shown in Table 4.

It can be seen from Table 4 that the system power supply reliability is the highest in the case of all action type monitoring terminals, and the lowest in the case of full manual, which is in line with the fact that the reliability of the circuit power supply is improved by the implementation of the distribution automation terminal. The traditional failure mode and effect analysis can only calculate the system power supply reliability under full manual conditions. Based on the power distribution reliability evaluation method of distribution automation, this paper can calculate the system power supply reliability when the switch adopts different power distribution terminal configuration schemes, with higher accuracy and more obvious difference.

### Table 4. Reliability index of scheme system in each terminal configuration

| Classification                  | SAIFI  | SAIDI  | CAIDI  | ASAI   |
|---------------------------------|--------|--------|--------|--------|
| All action type monitoring      | 0.6000 | 0.5740 | 0.9567 | 99.9934|
| terminals                       |        |        |        |        |
| CB1, CB2                         | 0.6000 | 0.6030 | 1.0050 | 99.9931|
| CB1, CB3                         | 0.6000 | 0.6030 | 1.0050 | 99.9931|
| CB1, CB2, CB3                    | 0.6000 | 0.6320 | 1.0533 | 99.9928|
| All standard monitoring          | 0.6000 | 0.7045 | 1.1742 | 99.9920|
| terminals                       |        |        |        |        |
| CB2, CB3                         | 0.6000 | 0.7045 | 1.1742 | 99.9920|
| CB1, CB3                         | 0.6000 | 0.7499 | 1.2498 | 99.9914|
The Subscript 3 means the switch with action type monitoring terminal, and the Subscript 2 means the switch with standard monitoring terminal.

5.2 Practical application of the algorithm
Take the example of Anhui Province. Considering the existing grid structure in Anhui Province, based on the calculation of the reliability evaluation results of different terminal configuration schemes in different wiring modes of different power supply areas, full consideration of economic and reliability requirements, the terminal configuration practicality in principle of Anhui area is obtained. See Table 5 for the number of action or standard monitoring terminals required for each circuit of each power supply zone.

Table 5. Configuration scheme of action or standard monitoring terminals in each power supply area

| Classification | Connection modes | All action monitoring terminals | All standard monitoring terminals | Monitoring terminals with action mix standard |
|----------------|------------------|---------------------------------|----------------------------------|---------------------------------------------|
|                | Cable net        |                                 |                                  |                                             |
| A              | Single-loop      | The action monitoring terminals are provided for section and interconnection ring network cabinets | —                               | —                                           |
|                | Single-contact   | The action monitoring terminals are provided for section and interconnection switch | —                               | —                                           |
|                | Double-contact   | The action monitoring terminals are provided for section and interconnection switch | —                               | —                                           |
| B              | Cable net        | Single-loop                     | 1                                | 2                                           |
|                | Single-contact   | 2                               | —                               | 1 +2                                        |
|                | Double-contact   | —                               | —                               | 2 +2                                        |
| C              | Cable net        | Single-loop                     | —                               | 2                                           |
|                | Single-contact   | —                               | —                               | —                                           |
|                | Double-contact   | —                               | 2                               | —                                           |
|                | Single-contact   | —                               | 2                               | —                                           |
|                | Double-contact   | —                               | 2                               | —                                           |
| D              | Overhead net     | Single-contact                  | —                               | 2                                           |
|                | Multiple-contacts| —                               | 2                               | —                                           |

In Class A, 50% of the circuits are still overhead, and only adding segments can not meet the reliability requirements. For the overhead circuits of the A-type area, it is recommended to implement the cable
transformation project in conjunction with the upgrading of the rural network to reduce the circuit failure rate and improve the reliability of the power supply. At the same time, through strengthening management, in-depth development of live detection and non-blackout operation distribution network management to improve power supply reliability. Typical wiring in Class B areas requires the configuration of automated terminals to meet reliability requirements. Typical wiring in category C area can meet the requirements of power supply reliability when no automation terminal is installed. However, in order to achieve considerable measurability and further improve power supply reliability, it is recommended to configure one standard monitoring terminal or fault indicator every 2km line. In order to meet the reliability requirements of the power supply in the D-type area, it is recommended to configure one basic monitoring terminal or fault indicator every 5km line. The results obtained in this paper are consistent with the guiding principles in The Guide of Planning and Design of Distribution Automation (Q / GDW 11184-2014). At the same time, it enriches the terminal configuration principles for different wiring modes in different power supply partitions and is more instructive.

6. Conclusion
According to the different functions of the switch in the reliability calculation process, this paper introduces the switch automation state factor, corrects the calculation formula of the load point power supply reliability index, and improves the distribution automation adaptability to the traditional failure mode and effect analysis. The analysis results of the example verify the correctness of the model and affirm the importance of the automation switch in improving the reliability of the distribution network. The results of the study show: the reliability of the 3km overhead line is 99.9934% for all action monitoring terminal, 99.9920% for all standard monitoring terminals, and 99.9881% for full manual operation. The reliability of different terminal configuration schemes is different. It can be seen that the more the number of configuration automation terminals, the higher the reliability of power supply; when the number of automatic terminals is the same, the more the number of action monitoring terminals, the higher the reliability of power supply. The action monitoring terminals and standard monitoring terminals have great differences in reliability improvement, price and implementation difficulty. If they can be flexibly used in the distribution network, the reliability of the power supply can be improved and the purpose of investment can be reduced.

7. References
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