Research on Operational Risk Index of Distribution Network with Distributed Generation

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Abstract. This paper analyses the distributed generation’s influence on failure severity index, introduces the index which can represent the probability of islanding and derive the distribution networks’ failure severity index with the connection of distributed generation. This paper analyses how the distributed generation influence distribution networks when the wide-area distributed generation connect with networks, then deriving the distribution networks’ failure severity index with the connection of wide-area distributed generation. Through analysing the same IEEE 33 node network and calculating traditional distribution networks’ reliability index and failure severity index, we can obtain the system's risk index. By comparing with every index in 3 different conditions, we can find that when the distributed generation connect with distribution networks, the networks’ risk tolerance has been improved, we can also find the significant improvement of distribution networks’ risk index when the wide-area distributed generation connect with distribution networks.

1. Introduction
The risk indicator is a combination of the possibility indicator of the risk and the risk consequences. For the risk assessment of the distribution network, it is necessary not only to assess the possibility of system failure, but also to quantitatively analyse the impact of system failure, that is, to analyse the severity index of the consequences of the failure. The possibility indicator of system failure is obtained by calculating the system reliability indicator, so another important part is to establish an indicator that can reflect the severity of the consequences of a failure in the distribution network. In the study, we evaluate the severity of the system's failure consequences from two aspects: load power loss rate and load number loss rate.

2. Impact of distributed power on distribution network
Today's distribution networks already have many distributed power sources. After the DG is connected to the distribution network, when the circuit breaker on the feeder fails, the load in the distribution network affected by the distributed power can be Distributed power supplies form islands, ensuring continuous power supply to these loads. [2]

In our research, distributed power is considered as random power. When a system fails, the probability of whether an island can be formed can be predicted and analysed based on the statistical data of the load size and the historical output data of the distributed power source. In the study of this paper, we assume that the probability of island formation with distributed power supply near the feeder.
when the distribution network is faulty is \( P \), and the load power loss rate index and load number loss rate index after the failure of the distributed power supply can be derived. It is shown by Formula (1) and Formula (2).\[3\]

\[
S_{LR} = \frac{\sum_{k=1}^{N_k} (\lambda_k \cdot L_k)(S_j \cdot u_i \cdot T_j) + \sum_{j=1}^{N_j} (1-P)(\lambda_j \cdot L_j)(S_j \cdot u_i \cdot T_j)}{\sum_{j=1}^{N_j} (S_j \cdot u_j)}
\] (1)

\[
C_{LR} = \frac{\sum_{k=1}^{N_k} (\lambda_k \cdot L_k)(N_j \cdot u_i \cdot T_j) + \sum_{j=1}^{N_j} (1-P)(\lambda_j \cdot L_j)(N_j \cdot u_i \cdot T_j)}{\sum_{j=1}^{N_j} (N_j \cdot u_j)}
\] (2)

In formulas (1) and (2), \( \varphi_{UGC} \) is the load set outside the distributed power supply range in the system, that is, the load set that is not affected by the distributed power supply; \( \varphi_{GC} \) is within the distributed power supply range of the system. The set of loads, that is, the set of loads within the isolated island that may be formed; the probability of \( P_i \) island. It is the probability that an orphan can be formed at the load point \( i \) when the system fails.\[4\]

We can deduce the load power loss rate index and load number loss rate index after the wide-area distributed power supply is connected to the distribution network, as shown in equations (3) and (4).

\[
S_{LR} = \frac{\sum_{k=1}^{N_k} (1-P)(\lambda_k \cdot L_k)(S_j \cdot u_i \cdot T_j)}{\sum_{j=1}^{N_j} (S_j \cdot u_j)}
\] (3)

\[
C_{LR} = \frac{\sum_{k=1}^{N_k} (1-P)(\lambda_k \cdot L_k)(N_j \cdot u_i \cdot T_j)}{\sum_{j=1}^{N_j} (N_j \cdot u_j)}
\] (4)

Formally, equations (3) and (4) are much simpler than equations (1) and (2), because all loads when the wide-area distributed power source is connected to the distribution network can be an island load.\[5\]

### 3. Establishment of Distribution Network Risk Index System

The distribution network risk assessment system should include three aspects: the probability of failure, the severity of the consequences of the failure, and the method of assessing the risk. We combine the failure rate and severity of failure consequence indicators of the distribution network to obtain the distribution network risk indicator Risk as shown in Equation (5).

\[
\text{Risk} = \text{SU} \cdot A_{SD} = \frac{\sum_{i=1}^{N_i} U_i}{\sum_{i=1}^{N_i} \times 8760} \times (p_1 \cdot S_{LR} + p_2 \cdot C_{LR})
\] (5)

In formula (5), SU is an indicator of power supply unavailability, which reflects the possibility of a system failure; \( A_{SD} \) is an indicator of the severity of a fault, reflecting the severity of the consequences of a system failure. Multiplying these two indicators to obtain a systematic risk indicator, the magnitude of the results is very small. However, this result not only reflects the probability of failure in the system, but also reflects the impact of the failure of the system, which has certain guiding significance for the evaluation and management of the distribution network.\[6\]In this paper, the risk level of the distribution network is simply divided into three types: general risk, medium risk, and serious risk. The risk level classification method is shown in Table 1.

| Degree of risk | Scope of risk |
|---------------|--------------|
| General risk  | 0–10⁻³       |
4. Example analysis

In this chapter, a typical IEEE33 node power distribution network is taken as an example. The influence of factors such as distribution network segmentation, contact transfer, and multi-loop power supply is considered. This network has 3 branch lines, 5 contact switches (indicated by dashed lines in the figure), and a total of 37 lines. Assume that the operating time of the switch is 0.5 hours, the failure rate of the line is 0.05 times / km / year, and the failure repair time of the line is 4 hours.

According to the idea of the failure mode impact analysis method, we need to first analyze the state of the system, determine the impact of each component failure, calculate the failure rate, failure repair time \( t \), failure outage time \( U \), and establish a failure mode and impact analysis table, such as Table 2 shows.

Table 2. Failure Modes and Impact Analysis of Partial Loads in Traditional Distribution Networks

| Node | (Times / Year) | \( t \) (Hour) | \( U \) (Hour/Year) |
|------|---------------|--------------|---------------------|
| 1    | 0.2           | 5.75         | 1.15                |
| 12   | 0.74          | 4.16         | 3.075               |
| 20   | 0.44          | 5.40         | 2.375               |
| 23   | 0.38          | 5.33         | 2.025               |
| 30   | 0.56          | 4.26         | 2.385               |

The above is the calculation of the system's reliability index, and we can get the probability of failure of the system, that is, the power supply availability rate \( SU \). Load power loss rate indicator after system failure \( (S_{LR}) \):

\[
S_{LR} = \frac{\sum_{k=1}^{N_k} \sum_{i \in \Phi_L} (\lambda_k \cdot L_k)(S_i \cdot u_i \cdot T_i)}{\sum_{j \in \Phi_L}(S_j \cdot u_j)} = 1.6294
\]  
(6)

Load number loss rate indicator \( (C_{LR}) \) after system failure:

\[
C_{LR} = \frac{\sum_{k=1}^{N_k} \sum_{i \in \Phi_L} (\lambda_k \cdot L_k)(N_i \cdot u_i \cdot T_i)}{\sum_{j \in \Phi_L}(N_j \cdot u_j)} = 1.6216
\]  
(7)

Severity index after system failure \( (A_{SD}) \):

\[
A_{SD} = \frac{1}{2} (S_{LR} + C_{LR}) = 1.6255
\]  
(8)

The system reliability index and the severity index after system failure are combined to obtain the system risk index:

\[
RISK = SU \cdot A_{SD} = 4.4376 \times 10^{-4}
\]  
(9)

We added a distributed power source to each of nodes 23 and 29 in the IEEE33 node system. Fault repair time \( t \), and fault shutdown based on the failure mode impact analysis method. Run time \( U \), and establish a failure mode and impact analysis table, as shown in Table 3.

Table 3. Failure modes and impact analysis of some nodes in the distribution network with distributed power

| Node | (Times / Year) | \( t \) (Hour) | \( U \) (Hour/Year) |
|------|---------------|--------------|---------------------|
| 1    | 0.2           | 5.75         | 1.15                |
| 12   | 0.74          | 4.16         | 3.075               |
According to the system failure mode and impact analysis table, we calculated the system's various reliability indicators as shown in Table 4.

Table 4. Reliability index of distribution network with distributed power

|        | ACI | CID | AITC | AIHC | AID | SU   |
|--------|-----|-----|------|------|-----|------|
| 20     | 0.44| 5.40|      |      |     | 2.375|
| 23     | 0.38| 3.16|      |      | 1.2 |      |
| 30     | 0.56| 2.86|      |      | 1.6 |      |

The island formation probability $P_i$ can be obtained from the distributed power output prediction and load prediction simulation curves. Here we take the island formation probability $P_i = 0.9$ to calculate the fault severity index. The results are shown in Table 5.

Table 5. Severity indicators of distribution network failures with distributed power

|        | $S_{LR}$ | $C_{LR}$ | $A_{SD}$ |
|--------|----------|----------|----------|
|        | 1.4990   | 1.4270   | 1.4630   |

Multiplying the reliability index of the distribution network and the severity index after the failure of the distribution network to obtain the risk indicator of the distribution network:

$$\text{Risk} = SU \cdot A_{SD} = 3.48 \times 10^{-4}$$ (10)

For the distribution network under the condition of wide-area distributed power access, also based on the failure mode impact analysis method, we first calculate the system failure rate, failure repair time $t$, failure outage time $U$, and establish a failure mode and impact analysis table, as shown in Table 6.

Table 6. Analysis of failure modes and impacts of some nodes in the distribution network under the conditions of wide-area distributed power access

| Node | (Times / Year) | $t$ (Hour) | $U$ (Hour/Year) |
|------|----------------|------------|-----------------|
| 1    | 0.2            | 1          | 0.2             |
| 12   | 0.74           | 1.35       | 1.0             |
| 20   | 0.44           | 3.64       | 1.6             |
| 23   | 0.38           | 3.16       | 1.2             |
| 30   | 0.56           | 2.86       | 1.6             |

According to the system failure mode and impact analysis table obtained in Table 6 and the derived reliability formula, we can calculate the reliability indicators of the distribution network as shown in Table 7.

Table 7. Distribution network reliability indicators under the conditions of wide area distributed power access

|        | ACI  | CID  | AITC | AIHC | AID  | SU    |
|--------|------|------|------|------|------|-------|
| 575    | 861  | 0.575| 0.861| 1.49 | 0.0000983|

When calculating the load power loss rate and load number loss rate after a distribution network failure under the conditions of wide-area distributed power access, we also need to first determine the
probability $P_i$ of the island formation in the distribution network when the distribution network fails. We assume the probability of island formation $P_i = 0.9$ to calculate the fault severity index. The results are shown in Table 8.

**Table 8.** Severity indicators of distribution network failures under conditions of wide-area distributed power access

|        | $S_{LR}$ | $C_{LR}$ | $A_{SD}$ |
|--------|----------|----------|----------|
|        | 0.16294  | 0.16216  | 0.16255  |

Multiplying the reliability index of the distribution network and the severity index after the failure of the distribution network to obtain the risk indicator of the distribution network:

$$\text{Risk} = SU \cdot A_{SD} = 1.598 \times 10^{-5} \quad (11)$$

By analysing and comparing the data in Table 9, the following conclusions can be drawn:

1. We found that the three indicators of total annual power outages (ACI) and average user power outages (AITC) in the three cases are the same. This is because in our calculation method, as long as the load is not powered by the main network, the load is considered to be in a “power outage” and is recorded as a power outage. This is an evaluation index given from the perspective of the power grid.

2. Load distribution loss index ($S_{LR}$), load number loss index ($C_{LR}$), and severity index ($A_{SD}$) after system failure of a distribution network with distributed power are lower than traditional power distribution. Net is small. For a distribution network connected to a wide area distributed power source, these three indicators are 10% of the traditional distribution network.

The probability of island formation in the power grid is directly related.

**Table 9.** Indicators in three cases of IEEE33 node network

| Index   | Traditional distribution network | Distribution network with distributed generation | Distribution network with wide area distributed generation |
|---------|----------------------------------|-------------------------------------------------|--------------------------------------------------------|
| ACI     | 575                              | 575                                             | 575                                                    |
| CID     | 2394                             | 2083                                            | 861                                                    |
| AITC    | 0.575                            | 0.575                                           | 0.575                                                  |
| AIHC    | 0.2394                           | 0.2083                                          | 0.861                                                  |
| AID     | 4.16                             | 3.62                                            | 1.49                                                   |
| SU      | 0.000273                         | 0.000238                                        | 0.0000983                                              |
| $S_{LR}$| 1.6294                           | 1.499                                           | 0.16294                                                |
| $C_{LR}$| 1.6216                           | 1.427                                           | 0.16216                                                |
| $A_{SD}$| 1.6255                           | 1.463                                           | 0.16255                                                |
| Risk    | 0.0004438                        | 0.000348                                        | 0.0001598                                              |
| Degree of risk | Moderate risk | Moderate risk | General risk |
5. Conclusion
Through the same IEEE33 node network, various reliability indicators and fault severity indicators of the traditional distribution network are analysed and calculated, and the system's risk indicators are obtained. According to the classification method, the risk degree of the distribution network in these three cases is classified. By comparing the calculated values of the indicators in these three cases, we can find that the distributed power supply network improves the risk level of the distribution network. We can also find that the wide area distributed power supply network is connected to the distribution network. Significant improvement from indicators.

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