Research on reliability evaluation of complex distribution network considering N-1 verification

Yuehao Yan¹, Wei Bao¹, Shuai Gao² and Quan Wang³*

¹Zhengzhou Power Supply Company, State Grid Henan Electric Power Company, Zhengzhou 450000, China
²Henan Ganneng Information Technology Limited Company, Zhengzhou 450000, China
³Henan Ganneng Information Technology Limited Company, Zhengzhou 450000, China
*Corresponding author’s e-mail: wangquanzhao@163.com

Abstract: With the rapid development of power system, the distribution network structure is gradually mature and the connection situation is more complex. The traditional distribution network reliability calculation method can not accurately calculate the reliability index of complex distribution network. Based on the traditional simple power supply reliability evaluation method of radial distribution network, this paper completely considers the influence of circuit breaker, tie switch, branch line, standby transformer and other equipment, and puts forward an improved network equivalence method model. The model first treats the complex distribution system in layers, and then gradually equates it into a simple radial distribution network to calculate the reliability of the system. At the same time, this paper analyzes the distribution network with multi connection structure in a provincial capital city. The results show that this model simplifies the complexity of distribution system reliability calculation, improves the accuracy and speed of reliability calculation, and more truly reflects the reliability of actual distribution system.

1. Introduction

The research on the reliability of distribution system is of great significance to improve the power supply performance of the system and respond to the power demand of users[1]. Therefore, reliability evaluation has become a routine work in distribution system planning and decision-making.

With the rapid development of power system, the radial distribution network is gradually connected, the power supply reliability is gradually improved, the distribution network structure is more and more complex, and the corresponding calculation steps of distribution network reliability become more and more cumbersome. The traditional reliability calculation method of distribution network generally only considers the radial grid structure, and ignores the influence of standby power supply and line connection on the reliability of distribution network.

Based on the traditional simple power supply reliability evaluation method of radial distribution network, this paper completely considers the influence of circuit breaker, tie switch, branch line, standby transformer and other equipment, and puts forward an improved network equivalence method model. The model first treats the complex distribution system in layers, and then gradually equates it into a simple radial distribution network to calculate the reliability of the system. At the same time, this paper...
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2. Reliability evaluation model and index of distribution system

2.1 Component mathematical model

In reliability evaluation, components can be divided into repairable components and non repairable components. Most of the components in the power system belong to repairable components. In the distribution system, repairable components mainly include circuit breaker, bus, overhead line, cable line, disconnector, fuse, load switch and distribution transformer[2]. For a distribution system element in use, it mainly has three states: normal operation, fault outage and planned maintenance. Since the reliability research of distribution network is based on whether to cause user’s power outage, planned maintenance and fault outage can be combined into fault state. The relationship between the parameters is:

\[ \lambda' = \lambda + \lambda'' \]  
\[ \gamma' = \frac{\lambda' \gamma' + \lambda'' \gamma''}{\lambda + \lambda'} \]  

In the above formula \( \lambda' \) is the failure outage rate, \( \gamma' \) is the troubleshooting time; \( \lambda'' \) is the planned maintenance rate, \( \gamma'' \) is the planned maintenance time; \( \lambda \) is the failure rate, \( \gamma \) is the repair time.

2.2 Reliability evaluation index

The distribution network reliability index used in this paper mainly includes two categories: load point reliability index and system reliability index.

(1) Reliability index of load point

In this paper, the principle of series parallel equivalence in network method is used to define and calculate the reliability index of load point in distribution network.

For a system composed of two or more components, if one of the components fails, the system fails. Only if all components are intact at the same time can the system be considered intact, then the system can adopt series equivalent.

Load point failure rate \( \lambda \) :

\[ \lambda = \sum_{i=1}^{n} \lambda_i \]  

Average outage duration per fault at load point \( \gamma \) :

\[ \gamma = \frac{\sum_{i=1}^{n} \lambda_i \gamma_i}{\sum_{i=1}^{n} \lambda_i} \]  

Average annual outage duration at load point \( U \) :

\[ U = \lambda \gamma \]  

For a system composed of two or more components, if all components fail, the system will fail. As long as one of the components works and the system is still in working state, the system can adopt parallel equivalence.

Load point failure rate \( \lambda \) :

\[ \lambda = \lambda_1 \lambda_2 \left( \gamma_1 + \gamma_2 \right) \]  

Average outage duration per fault at load point \( \gamma \) ;
\[
\gamma = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2}
\]  

(7)

(2) System reliability index

The average outage frequency index (SAIFI) of distribution network refers to the average number of outages suffered by each user powered by the system in unit time. It can be predicted by dividing the cumulative number of user power outages in a year by the total number of users supplied by the system:

\[
\text{SAIFI} = \frac{\sum_{i=1}^{n} \lambda_i N_i}{\sum_{i=1}^{n} N_i}
\]  

(8)

Where \(N_i\) is the number of users at load point \(i\), \(\lambda_i\) is the failure rate of load point \(i\).

The system average outage duration index (SAIDI) refers to the average outage duration of each user powered by the system in a year\(^{[3]}\). It can be predicted by dividing the total outage duration of users in a year by the total number of users powered by the system in that year:

\[
\text{SAIDI} = \frac{\sum_{i=1}^{n} U_i N_i}{\sum_{i=1}^{n} N_i}
\]  

(9)

Where \(U_i\) is the equivalent annual average outage time of load point \(i\).

The average service availability index (ASAI) of the system refers to the ratio of the total uninterrupted time obtained by the user to the total power supply time required by the user in a year:

\[
\text{ASAI} = \frac{8760 \sum_{i=1}^{n} N_i - \sum_{i=1}^{n} U_i N_i}{8760 \sum_{i=1}^{n} N_i}
\]  

(10)

Energy not service index (ENSI) refers to the total power outage of power outage load in the system:

\[
\text{ENSI} = \sum_{i=1}^{n} L_i U_i
\]  

(11)

Where \(L_i\) is the average load connected to blackout load point \(i\).

3. Network equivalence method considering N-1 verification

3.1 Principle of network equivalence method

In order to reduce the complexity of fault enumeration, the concept of equivalence is introduced into the model of network equivalence method, and an equivalent element is used to replace multiple elements with some common attributes. Network equivalence method mainly includes upward equivalence process and downward equivalence process\(^{[4]}\). As shown in Figure 1, there are four complex branch feeders in the distribution network, namely \(E_1, E_2, E_3, E_4\). After two equivalent transformations, it is transformed into the structure shown in Figure 2 and Figure 3.
3.2 Equivalent calculation process

Set minimum fault zone $Z_k$ contains $W$ sub area root nodes (including $W_1$ type I switches and $W_2$ type II switches), $x$ branches, $y$ load points and $z$ tie switches. The equivalent failure rate of each minimum failure zone can be calculated according to the reliability parameters of the component $\lambda_i[k]$, equivalent annual shutdown time $U_e[k]$, equivalent load $S_e[k]$ and total number of users $N_e[k]$. The calculation formula is as follows:

$$\lambda_e[k] = \sum_{i=1}^{W_1} \lambda_1[i_1] + \sum_{i_2=1}^{W_2} \lambda_1[i_2] + \sum_{j=1}^{x} \lambda_2[j] + \sum_{l=1}^{z} \lambda_3[l] + \sum_{k=1}^{y} \lambda_4[k] \times (1 - p_{fr}[k])$$  \hspace{1cm} (12)$$

$$U_e[k] = \sum_{i=1}^{W_1} (\lambda_1[i_1] \times r_1[i_1]) + \sum_{i_2=1}^{W_2} (\lambda_1[i_2] \times r_1[i_2]) + \sum_{j=1}^{x} (\lambda_2[j] \times r_2[j]) + \sum_{l=1}^{z} (\lambda_3[l] \times r_3[l])$$

$$+ \sum_{l=1}^{z} (\lambda_4[l] \times \lambda_5[l]) + \sum_{k=1}^{y} \lambda_{fr}[k] \times (1 - p_{fr}[k])$$  \hspace{1cm} (13)$$

$$S_e[k] = \sum_{i=1}^{f} S_{fr}[i]$$  \hspace{1cm} (14)$$

$$N_e[k] = \sum_{i=1}^{f} N_{fr}[i]$$  \hspace{1cm} (15)$$

Before analyzing the fault influence of the superior line on the subordinate line, first determine the power supply path of the subordinate area. The distribution network is generally open-loop operation, so the power supply path from the power point to each minimum fault area is unique[5]. The data structure of the minimum fault area contains the information of the parent area and the sub area. To determine the power supply path of the minimum fault area $Z_x$ under non fault conditions, according to the idea of the shortest path, search its parent area from the minimum fault area $Z_x$, then search the parent area of the $Z_x$ parent area, and search up level by level until the root node of the minimum fault area is the power source point. All the searched minimum fault areas are sorted according to the trend of power flow to form the power supply path of the minimum fault area $Z_x$. Referring to the idea of minimum path method, the influence of the minimum fault area not on the power supply path of $Z_x$ on the fault of load point in $Z_x$ can be converted into the minimum fault area on the power supply path. The phase of the minimum fault area on the non power supply path can be regarded as the lower level area of the minimum fault.
area on the power supply path. In the process of upward equivalence, the fault influence of the lower level area on the upper level area has been analyzed and the corresponding upward equivalent parameters have been calculated. Therefore, the fault influence of the minimum fault area on the non power supply path on Zx can be calculated directly by calling the upward equivalent parameters.

3.3 Parameter calculation of equivalent power point
Suppose that the power supply path of Z is successively connected in series by M+1 minimum fault areas, and is recorded as Z1, Z2...Zm according to the trend of non fault power flow. The set of upward equivalent node numbers of the minimum fault area Zjk (k = 1,2...m) is recorded as Φ(jk). The equivalent parameters of the S-th upward equivalent node are recorded as \( \lambda_{jkup}[S] \).

If Zj is the parent region of Zjk, Zjk and Zj are connected through the root node of Zj. Zj root node is section switch. In case of fault of section switch, it is the same fault shutdown area as Zjk. No matter whether there is a connecting line, Zjk load cannot be transferred, but in case of fault of other components in Zj except section switch, load transfer in Zj can be considered under the condition of connection, and the downward equivalent parameters shall reflect the difference between section switch and non switching components[6]. After Zj fault, the type of Zjk load point can be determined according to the load transfer path analysis:

If Zj is on the load transfer path, then:

\[
\lambda_j[i] = \lambda_e[jk] + \sum_{s \in \Phi(jk), s \neq r(jk)} \lambda_{jkup}[S]
\]

\[
U_j[k] = (\lambda_e[jk] - \lambda_r[jk]) \times t_s + \lambda_{root}[j] + \sum_{s \in \Phi(jk), s \neq r(jk)} \lambda_{jkup}[S]
\]

If Zj is not on the load transfer path, then:

\[
\lambda_j[k] = \lambda_e[jk] + \sum_{s \in \Phi(jk), s \neq r(j)} \lambda_{jkup}[S]
\]

\[
U_j[k] = U_e[jk] + \sum_{s \in \Phi(jk), s \neq r} \lambda_{jkup}[S]
\]

When Zj is a lower level region but not a sub region of Zjk, Zj and Zjk are not connected structurally. If there is a tie line and N-1 verification is met, Zj can transfer the load in case of any component failure in Zjk.

\[
\lambda_j[k] = \lambda_e[jk] + \sum_{s \in \Phi(jk), s \neq r(k+1)} \lambda_{jkup}[S]
\]

\[
U_j[k] = U_e[jk] + \sum_{s \in \Phi(k), s \neq r(k+1)} \lambda_{jkup}[S]
\]

According to the above calculation formula, the fault influence of all superior areas on Zj can be calculated, so as to obtain the equivalent parameters of the equivalent power point of Zj. The calculation formula is as follows:

\[
\lambda_j[i] = \sum_{k=1}^{m} \lambda_j[k]
\]

\[
U_e[j] = \sum_{k=1}^{n} U_j[k]
\]

Through the above formula, the reliability index of each load point and the reliability index of the whole system can be calculated.
4. Application instance

In this paper, taking a part of 10kV distribution system in a city as an example, the reliability of the proposed method is evaluated. Among them, line I and line II are outgoing from 35kV substation, and line III is outgoing from 110kV substation. Line II and line III are connected and meet N-1 verification. In case of failure, load transfer operation can be carried out between S6 and S9. The system shares 75 load points, 6347 users, and the average load is 19.676MW. The distribution network structure is shown in Figure 4.

Using the traditional network equivalence method and the network equivalence model considering N-1 verification to calculate the reliability index of the system, we get the following results:

| Load point | Traditional model | The model of this paper |
|------------|-------------------|------------------------|
| λ          | γ                 | U                      |
| 7          | 3.1472            | 0.9457                 | 2.9763 | 3.1472 | 0.9457 | 2.9763 |
| 13         | 3.2436            | 1.0254                 | 3.3260 | 3.2436 | 1.0254 | 3.3260 |
| 29         | 2.9367            | 1.5482                 | 4.5466 | 2.9367 | 1.5482 | 4.5466 |
| 51         | 2.8674            | 1.3596                 | 3.8985 | 2.8674 | 1.3596 | 3.8985 |
| 38         | 3.0691            | 1.152                  | 3.5356 | 3.0691 | 1.152  | 3.5356 |
| 44         | 2.8022            | 0.9917                 | 2.7789 | 2.8022 | 0.9917 | 2.7789 |
| 67         | 2.9535            | 1.4359                 | 4.2409 | 2.9535 | 1.4359 | 4.2409 |
| 72         | 3.1064            | 1.3407                 | 4.1648 | 3.1064 | 1.3407 | 4.1648 |

| Line | SAIFI | SAIDI | ASAI | ENSI | SAIFI | SAIDI | ASAI | ENSI |
|------|-------|-------|------|------|-------|-------|------|------|
| I    | 1.6742 | 4.3621 | 0.99843 | 31.7532 | 1.6742 | 4.3621 | 0.99843 | 31.7532 |
| II   | 1.8769 | 4.6775 | 0.99815 | 42.5484 | 1.4215 | 3.4176 | 0.99912 | 26.6135 |
| III  | 1.8242 | 4.5661 | 0.99847 | 37.7217 | 1.5019 | 3.6788 | 0.99922 | 22.1986 |

Figure 4. Structure of distribution system
Table 3. Reliability index of System

| Index | Traditional model | The model of this paper |
|-------|-------------------|-------------------------|
| SAIFI | 1.7233            | 1.5166                  |
| SAIDI | 4.4682            | 3.7425                  |
| ASAI  | 0.99836           | 0.99892                 |
| ENSI  | 112.0233          | 80.5653                 |

5. Conclusions
The reliability evaluation model of network equivalence method considering N-1 verification completely considers the influence of tie switch, standby power supply and load transfer on the reliability index of distribution network. The simulation results show that for the complex distribution network with single radiation, the index calculation results of the model in this paper are the same as those of the traditional model, but the calculation speed of the model in this paper is faster. For the distribution network with load transfer, the calculation results of this model are more accurate, which can truly reflect the reliability status of distribution network, and is of great significance to guide distribution network planning.

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