Power Supply Reliability Assessment Including Island Division and Network Reconfiguration

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Abstract. After the power distribution system (DS) fails, a single power supply recovery method will cause certain loads to fail to recover in time. To improve the reliability of distribution systems with distributed generation, this paper proposes a two-stage network restoration reliability assessment method considering island division and network reconfiguration. In the process of network fault recovery, firstly, distributed generation is used to supply power to the load point of power loss, islanding of the network after fault with the aim of minimizing power loss. Then the residual network is reconstructed and optimized by considering the network loss and voltage quality. Finally, the improved ieee33 node network is simulated based on Monte Carlo simulation method. The results show that this method is superior and can realize real-time load transfer, reduce power loss, improve the reliability of DS and the economy of system operation. Considering the continuous change of the network structure, the running state of the system can be described more accurately.

1. Introduction

Power system reliability refers to the ability to meet the user's continuous power demand in terms of power generation capacity and power quality [1]. According to the research data, 80% to 95% of power outages are mainly caused by DS failures [2]. DS reliability assessment methods generally fall into three categories: simulation method [3, 4], analytical method [5-7] and hybrid method [8]. In the simulation method, the reliability index is calculated by random sampling of the states of electrical components in the system [3] and based on the operating state system in the simulation duration. To obtain the accurate reliability index, the simulation method takes a lot of calculation and a long time [4]. The analytical method uses strict mathematical methods to calculate reliability, and the results have high reliability. However, due to the randomness of distributed power supply in DS, its reliability modeling has some limitations. The hybrid method combines the advantages of the two methods and can get more accurate results quickly [8].

In general, the DS mainly includes radial network and weak ring network. The radial network has the characteristics of unidirectional power flow and load splitter along the line, which is beneficial to the coordinated control of DS level protection devices. Nevertheless, compared with highly interconnected transmission systems, this radial topology reduces the reliability of DSs. Due to the unidirectional power flow of the radiant network, the failure of any component in the power supply
path may cause the interruption of power supply to the user. Therefore, the further away the load node from the power supply, the worse the reliability of power supply.

To enhance the reliability of DS, the reliability of load nodes can be improved by optimizing the network topology and reasonably configuring the distributed power supply. Network reconfiguration, that is, by changing the distribution network's partition and the state of the tie switch to change the distribution network's topology structure, the duration and probability of power supply interruption can be minimized, so as to improve the reliability of the DS and realize the purpose of reducing network loss, improving voltage quality and balancing load. In case of emergency, the distributed generation (DG) can realize the load transfer, it can also have a positive impact on the network reliability through the reasonable configuration and expansion of the DG. In the previous studies, the influence of network topology changes on power supply reliability was seldom considered in the related studies on the reliability evaluation of DG distribution network. Existing researches mainly focus on the optimization and reconstruction of distribution network [9-16] aiming at improving system reliability, e.g., a distribution feeder reconfiguration model with reliability as the optimization objective is proposed, and the model is analyzed and solved by particle swarm optimization (PSO) [11]. Li [12] proposed a reliability evaluation strategy with fault reconstruction, but only considered isolated island division of distributed power supply, without giving specific line reconstruction scheme. In order to reduce the power consumption of the system and improve the power quality, Naveen [15] proposed a fuzzy genetic algorithm for optimization and reconstruction.

Existing models may underestimate the reliability of the system for DG distribution networks with tie lines. Therefore, this paper proposes a reliability evaluation method which includes island division and network reconstruction. Considering the continuous change of network topology, the scheme of power supply recovery in stages can realize the timely transfer of load, shorten the outage time of load nodes to reduce power loss, improve the reliability of DS, reduce the operation times of line switches, and improve the economy of system operation.

2. Distribution Network Reliability Assessment

In general, the reliability of DS can be represented by various reliability calculation indexes [1]. Since the reliability evaluation is probabilistic, reliability indicators are usually estimated based on electrical component failure rates and time to repair.

2.1. Reliability Model of Transmission and Transformation Components

The components of the DS mainly include generators, transmission lines, transformers, circuit breakers, line switches, fuses, etc. For the operating state of components, the planned maintenance state of components is classified as the fault state in this paper, and only the two-state model including normal and fault of components is considered, as shown in figure 1.

In general, the normal operation duration and repair time of the element are considered to be exponentially distributed, so the failure rate and the repair rate are both constant. The normal operation duration $TTF_y$ and fault repair time $TTR_y$ [17] are shown in the following formula:

$$TTF_y = -\ln (R_1) / \lambda_y$$

$$TTR_y = -\ln (R_2) \cdot \mu_y$$

where, $R_1$ and $R_2$ are random numbers that follow a uniform distribution [0, 1]. The average failure rate of component $y$ is expressed as $\lambda_y$, and $\mu_y$ is its average failure repair time.
2.2. Reliability Model of DG and Load

Since both solar and wind energy resources are intermittent energy resources, their randomness and volatility need to be considered. Therefore, it is necessary to establish stochastic probability models of wind turbine and photovoltaic (PV) output power respectively.

2.2.1. Stochastic Model of Wind Power. The power output of the fan is generally related to the wind speed:

\[
P_{\text{wind}} = \begin{cases} 
0 & v \leq v_{ci}, v > v_{co} \\
a + bv & v_{ci} < v \leq v_r \\
P_r & v_r < v \leq v_{co} 
\end{cases}
\] (3)

where, \(v, v_{ci}, v_r, v_{co}\) are the actual, inlet, rated and cutting wind speed respectively; \(P_r\) is the rated output power of the fan, \(a\) and \(b\) are constant coefficients, \(a = \frac{v_{ci}}{v_r - v_{ci}}\), \(b = \frac{v_r}{v_r - v_{ci}}\).

Since the wind speed approximately follows the two-parameter Weibull distribution, and it is maintained between \(v_{ci}\) and \(v_{co}\) in most of the time, the probability density function of \(P_{\text{wind}}\) is [18]:

\[
f(P_{\text{wind}}) = \frac{k}{bc} \left( \frac{P_{\text{wind}} - a}{bc} \right)^{k-1} \exp \left( - \left( \frac{P_{\text{wind}} - a}{bc} \right)^k \right)\] (4)

Where \(k\) and \(c\) represent the shape parameter and scale parameter of Weibull distribution, respectively.

2.2.2. Stochastic Model of Photovoltaic Power. The output power of PV system can be expressed as:

\[
P_{\text{solar}} = r \sum_{m=1}^{M} A_m \eta_m = r A \eta
\] (5)

where, \(r\) is irradiance; \(A\) and \(\eta\) are respectively the total area of the square matrix and the photoelectric conversion efficiency; \(A_m\) and \(\eta_m\) are the values of a single battery module; \(M\) is the number of battery pack of solar cell square array.

In a certain period, the irradiance of sunlight can be approximately considered to follow the beta distribution [18], and the probability density function of the output of the \(P_{\text{solar}}\) can be obtained as follows:

\[
f(P_{\text{solar}}) = \frac{\Gamma(\alpha + \beta)}{R_M \Gamma(\alpha)\Gamma(\beta)} \left( \frac{P_{\text{solar}}}{R_M} \right)^{\alpha-1} \left( 1 - \frac{P_{\text{solar}}}{R_M} \right)^{\beta-1}
\] (6)

where, \(R_M = A \eta r_{\text{max}}\), is the maximum output power, and \(r_{\text{max}}\) is the maximum light intensity; \(\alpha\) and \(\beta\) are the shape parameters.

2.2.3. Load Random Model. The load demand at a certain time in the distribution network can be regarded as a random variable, and normally the normal distribution is used to approximate its probabilistic characteristics [18]:

\[
f(P_{Lp}) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left( -\frac{(P_{Lp} - \mu)^2}{2\sigma^2} \right)
\] (7)

where \(\mu\) is the average value of node load, and \(\sigma^2\) is the variance.
3. Multi-objective Reconfiguration Model of Distribution Network

Distribution network reconfiguration is a multi-objective and multi-constrained mixed integer optimization problem. In order to ensure the economic benefit and the power quality of the system operation, this paper takes the minimum network loss and node voltage deviation as the optimization goals.

3.1. Objective Function

The active network loss of the network is minimized as shown in equation (8).

\[ f_1 = \min P_{loss} = \min \sum_{i=1}^{M} \frac{P_i^2 + Q_i^2}{V_i^2} R_i \] (8)

where \( R_i \) is the resistance of branch line \( l \); \( P_i^2 \) and \( Q_i^2 \) are respectively the active power and reactive power flowing through branch \( l \); \( V_i \) is the node voltage of branch \( l \) terminal node; \( M \) is the number of branches.

The minimum voltage deviation of nodes in the network:

\[ f_2 = \min \Delta V_i = \min \{ \max \{ |1 - V_i| \} \} \] (9)

where \( V_i \) is the node voltage of node \( i, i = 1, 2, ..., N \), and \( N \) is the number of load nodes.

In this paper, by comparing the evaluation indexes and assigning weights respectively, the original complex problem can be simplified and solved. With \( f_1 \) as the first-level target and \( f_2 \) as the second-level target, the objective function can be optimized:

\[ f = \mu_1 f_1 + \mu_2 f_2 \] (10)

where \( \mu_1 \) and \( \mu_2 \) are the weights of the objective functions.

3.2. The Constraint

To ensure the safe and reliable operation of the DS, the reconstructed network must meet the power balance constraints, node voltage constraints, line capacity constraints and topology constraints of the distribution network, the constraints are as follows:

\[ P_i = P_{LP,i} + V_i \sum_{j=1}^{N} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \] (11)

\[ Q_i = Q_{LP,i} + V_i \sum_{j=1}^{N} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \]

\[ V_{i,\min} \leq V_i \leq V_{i,\max} \] (12)

\[ |S_i| \leq S_{i,\max} \] (13)

\[ N = M - N_G \] (14)

where \( P_i, Q_i \) are respectively the input active power and reactive power of node \( i; P_{LP,i} \), and \( Q_{LP,i} \) are respectively the active power and reactive power of the load node \( i; G_{ij}, B_{ij} \) and \( \delta_{ij} \) are respectively the conductance, susceptance and phase angle difference of nodes \( i \) and \( j; V_{i,\min} \) and \( V_{i,\max} \) are the upper and lower limits of allowable node voltage. \( S_i \) is the power flowing on branch \( i \) and \( S_{i,\max} \) is
the power limit for branch operation; $N$ and $N_G$ are the number of load nodes and power supply nodes in the network, respectively.

4. System Failure Recovery Strategy

4.1. Classification of Load Nodes and Division of Fault Areas
When the distribution network fails, the load points in the system can be divided into the following four categories according to the location of the fault and the relationship between DG output power and load demand. 1) The load point is always in the state of power loss before fault repair, and the power failure time is fault repair time. 2) The load point that can be transferred from DG to power supply after the failure. The power failure time is the fault isolation and the switch switching time of DG. 3) The load point of power supply can be restored through the contact line after the failure. The power outage time is the operation time of fault isolation and tie switch. 4) The load points that are not affected by faults.

4.2. Island Division Model
When something goes wrong on the network, the upstream line at the fault can maintain normal operation, while the downstream load point is affected by the fault into the power failure state. Based on the analysis of the system state after the failure, the following island division scheme is formulated: first, the power supply is restored by the DG, the fault area is divided into islands, and part of the load in the island area is recovered. The rest of the fault zone load is then restored through network reconfiguration.

The sequence of load point recovery is as follows: 1) give priority to power supply recovery for load points with high node importance; 2) second, restore the nodes with high demand for load; 3) finally, according to the distance between the load point and the DG, power supply will be restored from near to far. The division of isolated island area aims at obtaining the maximum load recovery amount:

$$\max \left( \sum_{m=1}^{G} \sum_{n=1}^{X_m} k_n \omega_n P_{LP,m,n}(t) \right)$$

where $k_n$ is the power supply coefficient, when the island region contains load point $n$, $k_n = 1$; otherwise $k_n = 0$; $\omega_n$ is the importance weight of node $n$; $P_{LP,m,n}(t)$ is the load demand at time $t$ of the node $n$ in the island region $m$; $X_m$ is the number of load nodes contained in island region $m$; $G$ is the number of islands formed.

In this paper, the load points in the isolated island region are only supplied by independent DG, and the output power and load demand of DG meet the following conditions:

$$\sum_{n=1}^{X_m} P_{LP,m,n}(t) \leq P_{DG,m}(t)$$

$$P_{DG,m}(t) \leq P_{DG,m,max}$$

where $P_{DG,m}(t)$ is the output power of DG $m$ at time $t$.

After the division of the island region in the first stage, the power supply is restored to the remaining power loss load points through network reconstruction. The network economy and power quality can be guaranteed by network optimization. To reduce the number of switching operations in the reconfiguration process, only the necessary switches required to satisfy the network radial constraints are closed for each reconfiguration, and normal operating lines are not processed. The multi-objective reconstruction model is optimized by the enumeration method to reduce network loss and node voltage deviation.
5. Reliability Evaluation Based on Monte Carlo Simulation (MCS)

The fault recovery schemes such as island partition and network reconstruction are considered comprehensively, and the single fault in the network is considered only. Based on MCS, the reliability assessment of distribution network is carried out. The steps are as follows:

1. Read the DS parameters, import the initial network topological structure of the DS, and number Y components in the distribution network;
2. Set the sequential Monte Carlo simulation year $T_{\text{seq}}$, and initialize the simulation clock $T_0$;
3. According to the network topology, obtain the connection matrix from the power node to each load node, as well as the component composition;
4. Sampling each component in the system to obtain its normal working time $TTF$, determining the smallest $TTF$ component $y$ as the fault component, and calculating its fault repair time $TTR_y$. The power loss node set $\psi$ in the system is determined according to the fault location. Then advance the analog clock to $T_y = T_0 + TTF_y + TTR_y$;
5. Obtain the random output of distributed power supply and the random power of load during fault repair through the random probability model; According to equations (10) and (11), the power loss area is divided into isolated islands, and the node set $\delta$ that can restore power supply through isolated islands is obtained;
6. According to the fault location, determine whether the power loss node outside the isolated island region can restore power supply through network reconstruction. If so, optimize the reconstruction model and output the optimal network topology;
7. According to the fault location, all nodes of the system are classified by combining the node set $\psi$ of power loss and the isolated island power supply set $\delta$, and calculate and record the number of power outages and power outage time at the load point;
8. Judge whether the simulation clock $T_0$ has reached the simulation period. If not, repeat steps (3)-(8), otherwise, end the simulation and calculate the system reliability index.

6. Analysis of Examples

This paper takes the improved ieee33 node system as an example. The original system consists of 37 lines (32 conventional lines and 5 tie lines) with 32 load points. Assuming the line length is 1km, the number of users at each load point is 1. And the incoming line of each load point in the network is equipped with a load switch (not shown in the figure) and is connected to the network via a feeder transformer. Circuit breakers are installed on the network branch lines (0-1, 1-18, 2-22, 5-25). The network topology is shown in figure 2. where, node 0 is the power node, the solid line represents the conventional line, and the dotted line represents the contact line.

![Figure 2. Improved IEEE33 node network.](image)

According to the importance of the load point and its average load demand, the power supply range of the DG in the system is divided as shown in table 1.
Table 1. Access location and supply area of DG in system.

| Type | DG locations | Maximum island power supply range and power supply priority |
|------|--------------|----------------------------------------------------------|
| T1   | 17           | 17, 16, 15, 14, 13                                       |
| WT2  | 12           | 12, 13, 14, 11, 10, 9                                    |
| PV   | 29           | 29, 30, 31, 32                                           |

Each node is equipped with a fan. The rated power of a single fan is 0.5MW. The inlet, rated and outlet wind speeds are 3, 13 and 25 m/s respectively, and the Weibull distribution parameters of wind speed are \( k=3.97 \) and \( c=10.7 \). The photovoltaic power generation system is composed of 3000 solar cell modules, each of which has an area of 2m², photoelectric conversion efficiency of 14%, and the beta distribution parameter value of irradiance is \( \alpha =2, \beta =0.8 \).

The operation time of the load switch is 0.05 hours [12]. In this paper, it is assumed that the load is transferred to the power supply of the DG at 0.05 hours, and the switching time of the contact switch is 1 hour. Regardless of the failure of switch and fuse elements, the breaking reliability is 100%. To simplify the calculation, the reliability parameters of other electrical components are shown in table 2, where the unit of line failure rate is \( (l/\text{km}\cdot \text{year}) \).

Table 2. Reliability parameters of main components of the system.

| Element   | Failure rate (l/year) | Average failure time (h) |
|-----------|-----------------------|--------------------------|
| Line      | 0.065                 | 5                        |
| Breaker   | 0.004                 | 4                        |
| Transformer | 0.015               | 10                       |

Based on MCS method, this paper analyzes the system reliability of the above distribution network in the following three cases, and the simulation life is 1000 years: Original case, only consider restoring the fault network by repairing components. Case 2, the DG is disconnected after the failure, and the power supply is restored through network reconfiguration. Case 3, after the failure, the DG will supply power to the power-losing load node, network reconfiguration will not be considered until the power supply is restored. The case of this paper, after the failure, the DG is connected to the power loss load to form an island to ensure the power supply in the area, then carry out network reconfiguration and optimization. The statistical results are shown in table 3.

Table 3. IEEE33 node system reliability index.

| Case     | SAIFI (l/year) | SAIDI (h/year) | CAIDI (h/year) | ASAI   | EENS (MW·h/year) |
|----------|----------------|----------------|----------------|--------|------------------|
| Original | 7.941          | 39.906         | 5.025          | 0.9954 | 228.315          |
| 1        | 6.635          | 19.816         | 2.987          | 0.9977 | 127.036          |
| 2        | 7.997          | 26.464         | 3.309          | 0.9970 | 159.358          |
| This paper | 6.609          | 14.178         | 2.148          | 0.9984 | 95.121           |

According to the reliability index of each case in table 3, there are significant changes in each index compared with the original case. In case 1, the ASAI index is improved, and the EENS index drops significantly, which indicates that the system reconstruction can effectively shorten the duration of power failure of users and reduce the power loss of the system. In case 2, only the DG supplies power to the load points that are disconnected from the system under the influence of failure, and the optimization range of each index is slightly smaller than other schemes. This is because DG power supply may be affected by output power fluctuations, and the scope of the island area is affected by the DG capacity, so it is impossible to guarantee the restoration of the power supply of all power-off loads. This problem can be solved by increasing the quantity and capacity of the DG in the system. In
the scheme proposed in this paper, the two optimization schemes are combined to improve the power supply capacity of the island range load in the event of a fault, while minimizing the system power consumption. At the same time, combined with network reconfiguration, the outage time of the load point outside the isolated island area can be effectively shortened.

7. Conclusion
To improve the reliability of DS, this paper proposes to combine the problem of island division with network topology optimization and apply it to the reliability evaluation of DS including DG. The example shows that the proposed method can improve the reliability of DS to the greatest extent and guarantee the economy and power quality of network operation at the same time.

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