Reliability Evaluation of Distribution System Considering Distributed Generation Correlation

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Abstract. The correlation between distributed generation (DG) can affect the reliability of distribution networks. To analyze the influence of this factor, first use Latin Hypercube Sampling, combine Spearman rank correlation coefficient and Cholesky decomposition to obtain the DG output power sample of the specified correlation coefficient. The bidirectional hierarchical structure reliability evaluation algorithm considering switch failure is used to evaluate the system. Considering the island operation mode of the distribution network after DG access, an improved heuristic load reduction strategy is proposed, and the reliability index of the load in the island is revised. The experimental results show that the reliability index of the system is closely related to the rated capacity of DG, the correlation between DG, and different load reduction strategies.

1. Introduction

In recent years, distributed generation (DG) has been widely used in power grid because of its remarkable benefits in energy conservation and environmental protection. On the one hand, the access of DG has changed the traditional operation mode, island operation has an impact on the reliability of power supply; on the other hand, the output of DG is uncertain, and the wind speed is related to the light intensity, so it is necessary to consider the correlation effect of DG output in the reliability research of distribution network.

At present, a lot of research has been done on the reliability of distribution network with DG. Ref. [1] evaluated the system reliability from the system average interruption duration and the system average interruption frequency index of the dispatchable and non-schedulable distributed generating unit distribution feeders. Refs. [2-3] established a reliability model of distribution network with DG based on sequential Monte Carlo simulation. Ref. [4] combined the probability reliability assessment with the dynamic simulation of the island, and considered the influence of the island on the voltage and frequency changes in the reliability assessment. Ref. [5] considered wind turbines, photovoltaic generators and energy storage technologies, and used Monte Carlo simulation to evaluate system reliability. Ref. [6] analyzed the reliability of large-scale battery storage systems, and performed reliability analysis on battery storage systems with different system configurations and management strategies. Ref. [7] simulated the correlation between multiple wind speeds under different probability distributions, but did not consider the application of photovoltaic generators. Ref. [8] analyzed the operating state and
reliability of the micro-grid island mode based on full-time-series simulated load and DG power characteristics, and proposed load reduction strategies based on the idea of block. This paper takes the transformed IEEE RBTS BUS6 system as an example to study the capacity of DG, the correlation between DGs, and the impact of different load reduction strategies on the reliability of the distribution network.

2. Correlation sample generation
The DGs in this paper are wind turbine generator (WTG) and photovoltaic generator (PVG). The probability distribution of wind speed follows the Weibull distribution, and the probability distribution of light intensity follows the Beta distribution. Because wind speed and light intensity obey non-normal distribution, Spearman rank correlation coefficient is used for characterization. The specific steps of generating correlation samples by combining Spearman rank correlation coefficient, Latin Hypercube Sampling (LHS) [9], and Cholesky decomposition are as follows:

Step 1. Divide the cumulative probability distribution function evenly into \( N \) intervals, randomly select any value for each interval, and perform inverse transformation to obtain the sample value of the interval; perform the above operations on \( M \) variables in turn to obtain the \( M \times N \) order initial Sample matrix \( P \);
Step 2. Perform a Cholesky decomposition on the rank correlation matrix \( \rho_{obj} \) obtained from the historical data of the variables, where \( H \) is a lower triangular matrix;
\[
\rho_{obj} = HH^T
\] (1)

Step 3. Generate a matrix \( R \) of order \( M \times N \) randomly, each row of the matrix \( R \) is composed of positive integers that are not greater than \( N \), and is not repeated. After calculating the rank correlation coefficient \( \rho_r \) and performing Cholesky decomposition, an intermediate matrix \( G \) is obtained;
\[
\rho_r = LL^T
\] (2)
\[
G = L^T R
\] (3)

Step 4. Update the matrix \( G \) to \( G_n \) according to the rank correlation of the matrix \( \rho_{obj} \), and then update the matrix \( R \) to \( R_n \) according to the arrangement order of the elements in each row in \( G_n \);
\[
G_n = HL^{-1} R
\] (4)

3. Reliability Evaluation Algorithm
With the increase of the complexity of the distribution network, the number of system components increases, and the traditional reliability evaluation algorithm has a low calculation efficiency. The bidirectional hierarchical structure reliability evaluation algorithm considering switch failure has high calculation efficiency, and considering the influence of switch failure, it can perform accurate reliability evaluation of the system. The specific steps of the algorithm are as follows:
Step 1. Block by circuit breaker or disconnector;
Step 2. Calculate the equivalent failure rate and duration of the component block;
Step 3. The head-end circuit breaker of the branch line is fused in the parent block, and other switch faults are fused in the downstream element block, and the reliability parameters are transmitted in the forward direction;
Step 4. The switch fault is accumulated to the adjacent adjacent downstream element block;
Step 5. The switch fault is fused in the downstream adjacent element block, and the reliability parameter is reversely transferred with the isolation switch block;
Step 6. Calculate the reliability index.

4. Reliability Evaluation of Distribution System Considering DG Correlation
### 4.1. Island operation

When the distribution network fails, a planned island can be formed by isolating the fault, and the power in the island can continue to be supplied by DG, which will affect the reliability of the load in the island. Since DG only continues to supply power to the loads in the isolated island, DG only affects the reliability of the load in the isolated island and has no effect on the reliability of the load outside the isolated island.

Considering that the output of DG is uncertain, only when the total output of DG in the island is greater than the total load in the island can the island be successfully formed. The probability of successful formation of the island is $P_{IS}$:

$$P_{IS} = \sum_{i=1}^{N} P\{ \sum_{1} P_{DG} > \sum_{1} P_{Li} \}$$

Where, $N$ is the sampling space, $\sum_{1} P_{DG}$ and $\sum_{1} P_{Li}$ are the total DG output and total load of the scenario $i$ in the island.

Only when the upstream main feeder element of the island fails, an island operation is formed, and only the fault condition of the upstream main feeder element of the island is corrected. $LP_{1}$ is set as any load in the island, $\lambda_{1}$ and $\lambda_{2}$ respectively represent the annual average fault frequency of $LP_{1}$ before and after modification, $U_{1}$ and $U_{2}$ respectively represent the annual average fault time of $LP_{1}$ before and after modification, and the reliability index of $LP_{1}$ after access by DG is modified as follows:

$$\lambda_{2} = \lambda_{1} - P_{IS} \sum_{i=1}^{m} \lambda_{ki}$$

$$U_{2} = U_{1} - P_{IS} \sum_{i=1}^{m} U_{ki}$$

Where, $m$, $\lambda_{ki}$ and $U_{ki}$ represent the number of main feeder elements, fault rate of each component and annual average fault time of the upstream of the island respectively.

### 4.2. Load reduction strategy

Since the output of DG is uncertain, when a fault occurs, it cannot guarantee that all loads in the island can be powered in any scenario, so it is necessary to cut off part of the load.

This article adopts an improved heuristic load reduction strategy: In order to improve the system reliability level, when the DG output is insufficient, the load point with the largest total load is preferentially reduced. If the DG output is still insufficient, the maximum load reduction continues Load point until the requirements are met. After considering the load reduction strategy, the reliability index of the load in the island needs to be revised:

$$\lambda_{3} = \lambda_{2} - \sum_{i=1}^{m} P_{Ci} \lambda_{ki}$$

$$U_{3} = U_{2} - \sum_{i=1}^{m} P_{Ci} U_{ki}$$

Where, $P_{Ci}$ is the probability of load $i$ restoring power supply under the load reduction strategy; $\lambda_{3}$ and $U_{3}$ are the load fault rate and the annual average fault time after the load reduction strategy, respectively.

In summary, the reliability assessment process of the distribution system considering the DG correlation is shown in Figure 1:
Figure 1. System reliability assessment process.

5. Case study
This article adopts the modified IEEE RBTS BUS6 system, which includes 1 bus, 23 fuses, 23 distribution transformers, 23 loads, 30 lines, 4 circuit breakers and 1 disconnector. Refer to ref. [10] for information on the reliability data, line length, and load data of each component. DGs are installed at feeders 53 and 59 to form planned islands as shown in Figure 2. The reliability indexes of the system mainly include: system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), average service availability index (ASAI), energy not supplied of system index (ENS). Set the LHS sampling size to 1000. Other specific parameters are as follows:

- Component failure rate: line 0.065 f / (yr·km⁻¹), circuit breaker 0.006 f / yr, disconnector 0.006 f / yr, transformer 0.015 f / yr;
- Component repair time: line 5 hr, circuit breaker 4 hr, disconnector 4 hr, transformer 200 hr. Isolation switch switching time 1 hr;
- The shape parameter of the Weibull distribution is 3.97, the scale parameter is 10.7, the cut-in wind speed of the fan is 3 m/s, the rated wind speed is 14 m/s, and the cut-out wind speed is 25 m/s;
- Beta distribution shape parameters $\alpha = 2.0$ and $\beta = 0.8$, the maximum light intensity of PVG is 600 W/m²;
5.1. The effect of DG capacity

Install one WTG and one PVG at feeders 53 and 59. The rated capacity of WTG and PVG is the same. The correlation coefficient between wind speed is 0.8, the correlation coefficient between light intensity is 0.8, and the correlation coefficient between wind speed and light intensity is -0.6. In the case of different DG rated capacities, the annual average blackout frequency of the system at some load points is shown in Figure 3.

Figure 2. IEEE RBTS BUS6 system diagram

Figure 3. Annual average fault frequency at each load point.

From Figure 3, we can see

1) With the increase of the DG rated capacity, the average annual fault frequency at each load point in the isolated island gradually decreases. It can be known that the access of DG can effectively improve the reliability index of the load in the island;

2) With the increase of DG rated capacity, the average annual fault frequency at the load point of LP16 remains unchanged. This is because the access of DG will only improve the reliability of load points in the isolated island range;

3) Because the load power at the LP8 load point is small, and the LP23 load point is large, the improved
heuristic load reduction strategy is adopted to preferentially reduce the load point with the larger load power when the DG output is insufficient. Compared with the LP23 load point, the LP8 load point improves the annual average fault frequency.

(4) In the initial stage of increasing the DG rated capacity, the annual average fault frequency at the load points in the island decreases rapidly, and as the DG rated capacity continues to increase, the annual average fault frequency at the load point in the island decreases slowly until saturation.

5.2. The effect of DG correlation
In order to better study the correlation of DG, the following three scenarios are set up in this paper. Set the rated capacity of each DG to 1.2MW.

- Scenario 1: all DGs are WTG, and the correlations between wind speed are 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8;
- Scenario 2: all DGs are PVG, and the correlations between light intensity are 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8;
- Scenario 3: each island is accessed to one WTG and one PVG, the correlation between wind speed is 0.8, the correlation between light intensity is 0.8, and the correlation between wind speed and light intensity is -0.1, -0.2, -0.3, -0.4, -0.5, -0.6, -0.7, -0.8.

The variation of ENS index with correlation in three scenarios is shown in Figure 4.

![Figure 4. Energy not supplied of system with different correlation coefficients.](image-url)

From Figure 4, it can be seen that
(1) According to scenario 1, as the positive correlation between wind speed and wind speed increases, ENS gradually increases. This is because the greater the positive correlation between wind speed and wind speed, the greater the possibility that the output power of the wind turbine will increase or decrease at the same time, resulting in a decrease in the reliability of the system;
(2) According to scenario 2, as the positive correlation between light intensity and light intensity increases, ENS gradually increases. This is because the greater the positive correlation between the light intensity and the light intensity, the greater the possibility that the output power of the photovoltaic generator increases or decreases at the same time, resulting in a decrease in the reliability of the system;
(3) According to scenario 3, as the negative correlation between wind speed and light intensity increases, ENS gradually decreases. This is because the greater the negative correlation between wind speed and light intensity, the less likely it is that the output power of the wind turbine and photovoltaic generator will increase or decrease at the same time, so the system reliability improves.

5.3. The effect of load reduction strategy
A comparative analysis of the reliability between the improved heuristic load reduction strategy (strategy 1) and the reduction strategy (strategy 2) considering the important coefficient of load [7] is conducted. The results are shown in Table 1.
Table 1. System reliability indicators under different load reduction strategies.

|_strategy  | SAIFI (fr/syst.cust) | SAIDI (hr/syst.cust) | CAIDI (hr/cust) | AISI | ENS (MWh/yr) |
|-----------|----------------------|----------------------|-----------------|------|--------------|
| strategy 1| 1.6677               | 9.4746               | 5.6813          | 0.9989 | 49.0619     |
| strategy 2| 1.7051               | 9.6613               | 5.6662          | 0.9989 | 49.3247     |

As can be seen from Table 1, the system reliability produced by using strategy 1 is better than strategy 2. This is because each time the load is reduced, strategy 1 only reduces the load point with the largest load each time, and sometimes can avoid cutting multiple load points, so the indexes are better.

6. Conclusions
(1) The access of DG can effectively improve the reliability index of the system, but with the increase of the rated capacity of DG, the improvement of the reliability index of the system is less and less obvious, and it may even reach saturation. Economic costs must also be considered when improving reliability indicators;
(2) The correlation between DG has an impact on the reliability index of the system. The reliability index of the system decreases as the positive correlation of the same type of DG increases, and increases as the negative correlation of different types of DG increases. The impact of the correlation between DGs should be considered in the reliability assessment;
(3) The improved heuristic load reduction strategy can effectively reduce the load, and the improved heuristic load reduction strategy has a greater advantage in improving system reliability.

7. References
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