

Reliability Evaluation of Distribution System with Distributed Generation

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Abstract. Distribution system reliability assessment is an important part of power system reliability assessment. In recent years, distributed generations (DG) are more and more connected to distribution system because of its flexible and friendly environment features, which imposes a great influence on distribution system reliability. Hence, a reliability evaluation method suitable for distribution system with DG is imperative, which is proposed in this paper. First, a probabilistic model of DG output is established based on the generation characteristics of DG. Second, the island operation mode of distribution system with DG is researched, subsequently, the calculation method of the probability of island successful operation is put forward on the basis of DG model and the load model. Third, a reliability assessment methodology of distribution system with DG is proposed by improving the traditional minimal path algorithm for reliability evaluation of distribution system. Finally, some results are obtained by applying the proposed method to the IEEE-RBTS Bus6 system, which are consistent with the well-known facts. In this way, the proposed method is proved to be reasonable and effective.

1. Introduction

Distribution system is directly connected with the customers, which has a great influence on the power supply reliability. Statistics show that most of the power outages are caused by the failure of distribution system, so the reliability evaluation of distribution system has been widely concerned. In recent years, distributed generations are more and more connected to the distribution system for its flexible and friendly-environment features, which changes the structure and operation mode of traditional distribution system and brings significant impact to the reliability evaluation of the distribution system [1].

At present, some researches have been made on the reliability evaluation of distribution system with DG. In reference [2], the island partition model is established according to the importance of load, based on which, the reliability evaluation model of distribution system with constant DG is proposed, but the impact of intermittent DG is not considered. A three-state model of DG output is presented in [3], however, the variation range of intermittent DG output is large and three state can't accurately reflect the DG's actual state. In reference [4], multi-state output power model of wind turbine is researched and the reliability of distribution system is assessed using the minimal cut set method, which does not consider the effect of different types of DG on distribution system. In reference [5], Monte Carlo simulation method is used to calculate the reliability of distribution system with DG, which takes a long time.



In this paper, a probabilistic model of DG output is established through the research on the generation characteristics of DG. Then the calculation method of probability of island successful operation is put forward based on DG model and the load model of the island. Finally, the reliability of distribution system with DG is evaluated by improved minimal path algorithm.

2. Reliability model of DG and load

2.1. Model of traditional DG

Traditional DG (e.g., diesel generator, micro gas turbine) is based on fossil fuels, whose output power is stable and continuously adjustable and can be represented by two state model: when DG fails to work, its output power is 0 and the corresponding probability is the unit forced outage rate (FOR); when DG works normally, its output power is the unit rated power (P_{rated}) and the corresponding probability is (1-FOR). Output power probability model of traditional DG is shown in Table 1.

Table 1. Output power probability model of traditional DG

Level of output power	Output power	Probability
1	0	FOR
2	P_{rated}	1-FOR

2.2. Model of renewable DG

Renewable DG (e.g., wind turbine generator, photovoltaic power generation) is much more complicated than the traditional DG. Both the unit forced outage rate and the uncertainty of output power of renewable DG should be considered. Due to the intermittent nature of renewable energy, the renewable DG output power is uncertain. In this paper, output power probability model of wind turbine generator (WTG) is considered. The output power of WTG is affected by two factors: wind speed distribution and output power characteristic of the selected WTG.

2.2.1. Model of wind speed distribution. Weibull distribution model is one of the most commonly used models for simulating wind speed distribution. And the weibull probability density function is expressed as:

$$f(v) = (k/c) \cdot (v/c)^{k-1} \cdot \exp\left[-(v/c)^k\right] \quad (1)$$

Where $k = (\sigma/v_m)^{-1.086}$ is called the shape parameter, $c = v_m / \Gamma(1+1/k)$ is called the scale parameter, v_m and σ represent the mean and standard deviation of the local wind speed, respectively.

2.2.2. Output power characteristics of WTG. Output power characteristic curve of WTG describes the relationship between the output power and the wind speed, which can be represented by the rated power (P_{rated}), cut-in wind speed (v_{ci}), rated wind speed (v_r) and cut-out wind speed (v_{co}) of the WTG. The relationship between output power of WTG ($P(v)$) and the wind speed (v) can be expressed as:

$$P(v) = \begin{cases} 0 & 0 \leq v \leq v_{ci} \\ P_{rated} \frac{v - v_{ci}}{v_r - v_{ci}} & v_{ci} \leq v \leq v_r \\ P_{rated} & v_r \leq v \leq v_{co} \\ 0 & v_{co} \leq v \end{cases} \quad (2)$$

2.2.3. Output power probability model of WTG. Output power of WTG is uncertain and two-state model can't accurately reflect the actual output state of it. Thus, multi-state model that can reflect the output power level of renewable DG is necessary. Output power of WTG is directly related to wind speed, so it can be calculated using the local statistical wind speed information within one year. As the wind speed range is large, the real-time wind speed is insteaded by average hourly wind speed in this paper. Wind speed is divided into several levels with the interval of 1m/s. Then the output power state

and the corresponding probability of WTG can be obtained according to the output power characteristics and the local wind speed distribution. Output power probability model of a type of WTG is shown in Table 2.

Some relevant parameters are as follows:

Parameters about the WTG: P_{rated} is 1MW, v_{ci} is 4m/s, v_r is 14m/s, v_{co} is 25m/s.

Information about the local wind speed: v_m is 10.0643m/s, σ is 4.8426m/s.

Table 2. Output power probability model of WTG

Level of output power	Wind speed (m·s ⁻¹)	Output power as a percentage of the rated power	Probability
1	0~4 or >25	0	0.0977
2	4~5	5%	0.0556
3	5~6	15%	0.0660
4	6~7	25%	0.0738
5	7~8	35%	0.0788
6	8~9	45%	0.0808
7	9~10	55%	0.0799
8	10~11	65%	0.0763
9	11~12	75%	0.0707
10	12~13	85%	0.0636
11	13~14	95%	0.0555
12	14~25	100%	0.2013

2.3. Load model

The annual time series load model [6] is used in this paper, based on which, the load level is divided into several grades using the clustering technique. It is verified that in order to balance the calculation precision and time, the load level can be divided into 10 grades [7].

3. Probability of island successful operation

Distribution system has become a multi-power network with DG connected to it and islanding becomes a new operation mode of distribution system. Under normal circumstances, the main power and DG supply for the load. In the case of a fault, the circuit breaker and associated control components start to operate, leading to the separation of the partial distribution system containing DG from the main distribution system. Then DG can still supply for its independent distribution system, thus forming an island. However, the island can't operate successfully in any case after it is formed. Only when the output power of DG is greater than or equal to the load demand in the island and the DG works normally, can the island operate successfully, otherwise the island will fail to operate.

In this paper, the probability of island successful operation (ρ_{so}) is calculated based on DG model and the load model mentioned above, and some provisions are made as follows: 1) only when the output power of DG is greater than or equal to the load demand, can the island operation be carried out; 2) any DG in the island fails to work, the island fails to operate; 3) during the normal operation of distribution system, the load in the original planned island can be supplied by both the main power and the DG at the same time, and when the distribution system gets fault, the DG can supply the load in the planned island continuously. Thus, ρ_{so} can be calculated as:

$$\rho_{so} = \prod_{g=1}^{N_g} (1 - \rho_g) \cdot \sum_{s=1}^{N_s} \frac{\max\{P_s^g - P_s^d, 0\}}{P_s^g - P_s^d} \rho_s \quad (3)$$

where $N_s = \prod_{i=1}^{N_d} nl_i^d \prod_{j=1}^{N_g} nl_j^g$ represents the total number of combinations of all possible states of all

loads and DGs in the island, N_d is the number of all load points (LPs) in the island, N_g is the number of all DGs in the island, nl_i^d represents the number of load levels of LP i , nl_j^g represents the number of output power levels of DG j , P_s^d and P_s^g respectively represent the total amount of load and DG output

power in the island at the s -th combination state, ρ_g is the failure rate of DG g ,

$\rho_s = \rho_{1,l}^d \rho_{2,l}^d \cdots$ represents the probability of the s -th combination state.

4. Reliability evaluation of distribution system with DG

4.1. Reliability indices

Reliability indices of distribution system is an important criterion and basis for measuring system reliability [8], which can be usually divided into two levels: load point reliability indices and system reliability indices.

Load point reliability indices reflects the power supply reliability of a single load point, which include failure rate (λ), average outage time (γ) and annual outage time (U). The reliability indices of LP i are calculated as:

$$\lambda_i = \sum \lambda_{i,k} \quad (4)$$

$$U_i = \sum (\lambda_{i,k} \cdot \gamma_{i,k}) \quad (5)$$

$$\gamma_i = U_i / \lambda_i \quad (6)$$

Where $\lambda_{i,k}$ and $\gamma_{i,k}$ represent the failure rate and repair time of component k that has effect on the reliability of LP i .

In the distribution system with DG, the island is formed when failure occurs, and DG still supply for the LP within the island, reducing the LP's failure rate and outage time. As for the LP outside the island, DG has no effect on it. Thus, reliability indices of LP j within the island are calculated as:

$$\lambda_j = \rho_{so} \lambda_j' + (1 - \rho_{so}) \lambda_j'' \quad (7)$$

$$U_j = \rho_{so} U_j' + (1 - \rho_{so}) U_j'' \quad (8)$$

$$\gamma_j = U_j / \lambda_j \quad (9)$$

Where λ_j' and U_j' respectively represent the failure rate and annual outage time of LP in the island when the island succeed to operate, λ_j'' and U_j'' respectively represent the failure rate and annual outage time of LP in the island when the island fails to operate.

System reliability indices reflects the power supply reliability of the whole distribution system, and the typical indices include system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption frequency index (CAIFI), customer average interruption duration index (CAIDI), and average service availability index (ASAI). Some indices used in this paper are calculated as:

$$SAIFI = \frac{\sum_{i=1}^{n_{LP}} (N_i \cdot \lambda_i)}{\sum_{i=1}^{n_{LP}} N_i} \quad (10)$$

$$SAIDI = \frac{\sum_{i=1}^{n_{LP}} (N_i \cdot U_i)}{\sum_{i=1}^{n_{LP}} N_i} \quad (11)$$

$$ASAI = \frac{8760 \sum_{i=1}^{n_{LP}} N_i - \sum_{i=1}^{n_{LP}} (U_i \cdot N_i)}{8760 \sum_{i=1}^{n_{LP}} N_i} \quad (12)$$

Where n_{LP} is the number of LP, N_i is the number of customer connected to LP i .

4.2. Reliability evaluation of distribution system based on improved minimal path method

When distribution system with DG gets a fault, the circuit breaker and associated control components start to operate, forming an island. DG in the island still supply for its load, thus the power supply reliability of the load within the island is improved. For the load outside the island, DG has no effect on its reliability. In this paper, traditional minimal path method [9] is improved, which is suitable for reliability calculation of distribution system with DG. The basic idea of the improved minimal path method is as follows:

Step1: First of all, get the minimal path of each LP to the main power. All the components in the system are divided into two parts: the minimal path components and the non-minimal path components.

Step2: Determine the type of LPs according to the island partition. For LPs outside the island, calculate the reliability indices using the traditional minimal path method. For LPs within the island, calculate the reliability indices using the improved method described as below.

For the minimal path components:

a. If the component is within the planned island and it gets fault, the DG in the island automatically stop working. The LPs are not supplied due to the failure of component and the outage time is the component's repair time.

b. If the component is outside the planned island and it gets fault, the island breaker and associated control components automatically operate and the island will operate with a certain probability. If the island succeeds to operate, the island LPs will be supplied by DG and the component failure has no effect on the reliability of the LPs; if the island fails to operate, the island LPs will be unsupplied and the outage time is the component's repair time.

For the non-minimal path components:

c. If the component of the load branch to which LP is not connected gets fault, the fuse connected to the load branch automatically work, and the LP reliability is not affected.

d. For the non-minimal path component on the main feeder and the branch feeder, search for the upstream breaker and switch nearest to it, then determine the effect of the component failure on the LP reliability according to the position of circuit breaker and switch.

d1. If breaker is not on the LP minimal path and the component gets fault, the breaker will be automatically disconnected and the LP reliability is not affected.

d2. If breaker is on the LP minimal path and switch is not on the LP minimal path, the effect of the component failure on the LP reliability is similar to case **b** above, and the difference is that when the island fails to operate, the LP outage time is the switch operation time.

d3. If breaker is on the LP minimal path and switch is also on the LP minimal path, the effect of the component failure on the LP reliability is the same as case **b** above.

Step3: Calculate LP reliability indices based on the above cases, and then calculate the system reliability indices.

5. Case study

5.1. Case data

In this paper, taking the main feeder F4 of IEEE-RBTS Bus6 system [10] as an example to evaluate the reliability. There are 23 load points, 1 disconnecting switch, 23 distribution transformers, 23 fuses and 4 circuit breakers in the system. The original data and reliability parameters of each component are consistent with that in [10].

It is considered to combine the WTG with some diesel generators to supply for the island load. That is, DGs connected to the distribution system contain both traditional DG and renewable DG. The failure rate of diesel generator and WTG are 0.02 and 0.04, respectively.

Connecting DG to branch line 19 and 25, respectively. When failure occurs in the distribution system, island breaker and associated control components start to operate, then island 1 and island 2 will be formed, as shown in Figure 1. Assuming that each LP is at the same level at a time, the island load level classification and the corresponding probability are shown in Table 3.

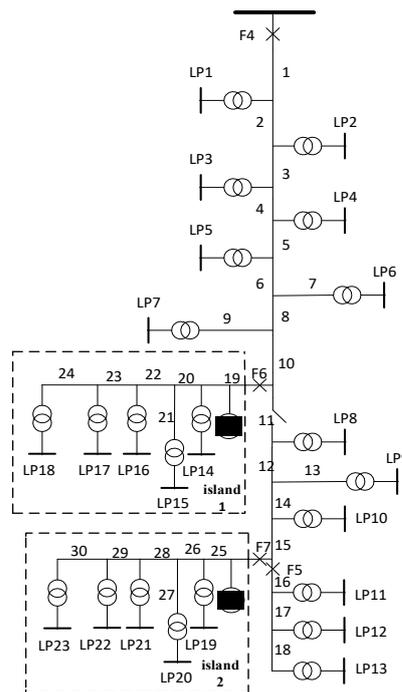


Figure 1. Connection diagram of distribution system with DG

Table 3. Load level and the corresponding probability

Island 1		Island 2	
Load (kW)	Probability	Load (kW)	Probability
2400.90	0.0001	2597.20	0.0001
2140.16	0.0429	2315.14	0.0429
1968.50	0.0992	2129.44	0.0992
1816.28	0.1079	1964.78	0.1079
1653.02	0.1411	1788.17	0.1411
1510.41	0.1598	1633.90	0.1598
1346.18	0.1223	1456.25	0.1223
1197.09	0.1477	1294.96	0.1477
1039.59	0.1165	1124.59	0.1165
869.61	0.0625	940.71	0.0625

5.2. Study results

In this paper, the reliability evaluation of distribution system with DG is researched based on the following several scenarios.

1) scenario 1: evaluate the reliability of distribution system without DG.

2) scenario 2: connect DG to island 1, where the rated capacity of WTG is 1000kW and the capacity of diesel generator is 50% of the island peak load.

3) scenario 3: connect DG to island 2, where the rated capacity of WTG is 1000kW and the capacity of diesel generator is 50% of the island peak load.

4) scenario 4: connect DG to island 2, where the rated capacity of WTG is $2 \times 1000\text{kW} = 2000\text{kW}$ and the capacity of diesel generator is 50% of the island peak load.

5) scenario 5: connect DG to island 2, where the rated capacity of WTG is 1000kW and the capacity of diesel generator is 20%, 40%, 60%, 80%, 100% of the island peak load, respectively.

According to equation (3), calculating the ρ_{so} of scenario 2~5, respectively. And the ρ_{so} of scenario 2,3,4 is 0.7123, 0.6844, 0.8205, the ρ_{so} of scenario 5 is shown in Table 4.

Table 4. Probability of island successful operation in scenario 5

Percentage of diesel generator capacity of island peak load	20%	40%	60%	80%	100%
ρ_{so}	0.1620	0.5062	0.8253	0.9764	1

Calculating the reliability indices using the proposed evaluation method. Some load points' reliability indices are shown in Table 5 and Table 6, and the system reliability indices are shown in Table 7. (scenario 5.1~5.5 corresponds to the five cases in scenario 5)

Table 5. Failure rate index of some load points

Scenario	LP1	LP6	LP9	LP15	LP20
1	1.6725	1.7115	1.7115	2.5890	2.5598
2	1.6725	1.7115	1.7115	1.4083	2.5598
3	1.6725	1.7115	1.7115	2.5890	1.4253
4	1.6725	1.7115	1.7115	2.5890	1.1998
5.1	1.6725	1.7115	1.7115	2.5890	2.2913
5.2	1.6725	1.7115	1.7115	2.5890	1.7207
5.3	1.6725	1.7115	1.7115	2.5890	1.1918
5.4	1.6725	1.7115	1.7115	2.5890	0.9413
5.5	1.6725	1.7115	1.7115	2.5890	0.9022

Table 6. Annual outage time index of some load points

Scenario	LP1	LP6	LP9	LP15	LP20
1	8.4015	8.5965	11.4825	12.9840	15.7237
2	8.4015	8.5965	11.4825	9.1364	15.7237
3	8.4015	8.5965	11.4825	12.9840	10.0516
4	8.4015	8.5965	11.4825	12.9840	8.9239
5.1	8.4015	8.5965	11.4825	12.9840	14.3815
5.2	8.4015	8.5965	11.4825	12.9840	11.5287
5.3	8.4015	8.5965	11.4825	12.9840	8.8839
5.4	8.4015	8.5965	11.4825	12.9840	7.6316
5.5	8.4015	8.5965	11.4825	12.9840	7.4362

Table 7. System indices

Scenario	SAIFI	SAIDI	ASAI
1	1.9778	11.0747	0.998736
2	1.8201	10.5608	0.998794
3	1.8263	10.3171	0.998822
4	1.7962	10.1665	0.998839
5.1	1.9420	10.8954	0.998756
5.2	1.8658	10.5144	0.998800
5.3	1.7951	10.1611	0.998840
5.4	1.7617	9.9939	0.998859
5.5	1.7564	9.9678	0.998862

Some results can be obtained as follows by analysing the calculation results of reliability indices.

1) Effect of DG on the reliability

It can be obtained by comparing reliability indices of scenario 1 and the other scenarios that: after DG is connected to the distribution system, reliability indices of load points outside the island have no changes; the failure rate and annual outage time of load points within the island are all reduced; and the system indices are also improved.

2) Effect of DG position on the reliability

It can be obtained by comparing the calculation results of scenario 2 and scenario 3 that: the improvement of system indices (except for SAIFI) when DG is connected to island 2 is better than that when DG is connected to island 1, which shows that the more the DG is closer to the end of feeder, the more obvious the system reliability is improved.

3) Effect of DG capacity on the reliability

By comparing the calculation results of scenario 3 and scenario 4, or the various cases of scenario 5, it can be obtained that: with DG (WTG or diesel generator) capacity increases, probability of island successful operation increases, at the same time, the reliability improves but the degree of improvement is getting smaller and smaller.

4) Effect of DG intermittency on the reliability

It can be obtained from the calculation results of scenario 3, scenario 4 and scenario 5.5 that: when WTG capacity and diesel generator capacity increases at the same ratio, the latter one is better than the former one in the degree of improvement for the distribution system reliability. It shows that the contribution of WTG to the system reliability is less than that of diesel generator, which reflects the adverse effects of intermittency of the renewable DG.

6. Conclusions

The structure and operation mode of traditional distribution system are changed as DG is connected to it, which presents a new challenge to the reliability evaluation of distribution system. In this paper, a probabilistic model of DG output is established. Then the calculation method of probability of island successful operation is put forward based on DG model and the load model. Finally, the reliability of distribution system with DG is assessed by the improved minimal path algorithm. By applying the proposed method to a typical distribution system, some results are obtained which are consistent with the well-known facts, thus, the proposed method is proved to be reasonable and effective. The results are as below: 1. Accessing DG to distribution system can improve the reliability of load point of the island and whole system; 2. The more the DG is closer to the end of feeder and the greater the DG capacity is, the more obvious the system reliability is improved; 3. Traditional DG has a better improvement on the distribution system reliability compared to renewable DG.

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