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Reliability Assessment of Distribution Networks with Distributed Generations Using Monte Carlo Method

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Abstract

As the development of smart grid, more and more distributed generations (DGs) are introduced to the distribution networks in the power system. This paper presents a Monte Carlo method for calculating the reliability of the distribution system with DGs. To begin with, the models of DGs and the islanding schemes are discussed. Applying Monte Carlo stimulation, the paper puts forward a new method for system failure state assessment based on minimal path and zoning concepts. An example based on IEEE-RBTS Bus6 is applied to study the impacts brought by DGs to the distribution system, taking a lot of elements into consideration such as models of DGs, switch devices configuration, multiple accidents and islanding strategies.

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Keywords: Distribution system, reliability, distributed generation, Monte Carlo

1. Introduction

With the increasing pressure of environmental issues and desire for lower-carbon economy, the development of smart grid is an inevitable trend for many countries. As a very important part of the smart grid, distributed generations (DGs) most of which are based on renewable energy are widely introduced to the present power distribution system. Normally, distributed generation is defined as generation located in transformer substation, distribution feeder or customer, and whose capacity is less than 10MW. Although these distributed energy resources have many advantages such as small investment, environmental friendly and high flexibility, they also changed the structure of the traditional distribution system and brought many uncertainties to the present system.

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To begin with, the direction of the power flow in the distribution network which is usually fixed in tradition distribution system could be reversed in certain operation condition when DGs are plugged into the system, which changes the structure of the tradition distribution system. Secondly, the output of these DGs are largely depend on energy resources such as wind, sunlight and water flow, which are well-recognized for their unpredictability and subject to a variety of elements. Due to the uncertainty of these DGs' output, the power quality and reliability of the distribution system may experience great challenges such as frequency offset and voltage fluctuation. As a result, both the theory and calculation method for reliability assessment of distribution systems with DGs should be updated.

So far, many theories and methods have been introduced. Generally, there are two methods for distribution reliability calculation: analytical methods and stimulation methods, both of which are classic. Reference [1] proposed a multi-state DG model and discussed the failure rate of DG components. During the procedure of the reliability assessment, Reference [2] took the islanding probability into consideration. Combining the multi-state DG model and islanding strategy, [3] proposed a revised minimal path method to analyze the impacts of DGs plugged into the distribution system. Reference [4] used Monte Carlo stimulation to calculate the reliability, but ignored the existent of DGs. Reference [5] discussed the impacts brought by DGs from aspects of islanding operation and switch configuration, and illustrated the idea through a very simple example.

The reliability of the distribution system with DGs is calculated using a Monte Carlo method. A new automatic method is proposed for failure state analysis after Monte Carlo simulation, and discusses the reliability of the distribution system in different DG models and switch devices, considering multiple accidents under certain islanding scheme. An example based on IEEE RBTS Bus6 is applied to test the theory.

2. DG Modeling

Different kinds of DGs and its modeling could influence the reliability assessment of the system greatly, thus traditional generation model could not be applied for DG directly. This part of the paper would study how to build a suitable DG model.

Due to the variety of DGs, different DG types result in different DG modeling. To begin with, most DGs are less than 10MW, thus cannot be modeled as infinite power resources. Moreover, DGs are well-known for its output uncertainty. For example, wind-based distributed generation involves great uncertainty in power output, due to the changes of wind speed. As a result, DG cannot be modeled as traditional power unit, which is much more stable and easier to control.

Considering all the characteristics of DGs, a multi-state model could meet the properties for most DGs when applying Monte Carlo stimulation. Taking wind-based generation as an example, the power and wind relation of N wind turbines refers to (1).

$$C_T(v)=\begin{cases} 0 & 0\le v\le v_{ci} \\ a+bv^m & v_{ci}\le v\le v_r \\ R & v_r\le v\le v_{co} \\ 0 & v\ge v_{co} \end{cases} \tag{1}$$

where a,b are constants; $C_T(v)$ is the total power output of wind turbines; v_{ci} is the cut in wind speed, m/s; v_r is the rated wind speed, m/s; v_{co} is the cut out wind speed, m/s; R is the total rated capacity of N wind turbines.

Although Weibull wind speed distribution function does not reflect the cumulative frequency information, the loads data could help to build an approach to calculate the cumulative frequency distribution of wind speed, when parameters of Weibull wind speed distribution are given. [1] Fig. 1 shows the data of wind speed according to Weibull distribution during 8760 hours, where c=10.0 and k=2.8.

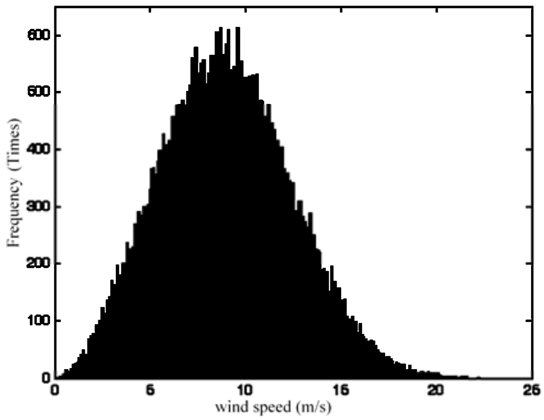

Fig. 1.Weibull Wind speed statistics by distribution

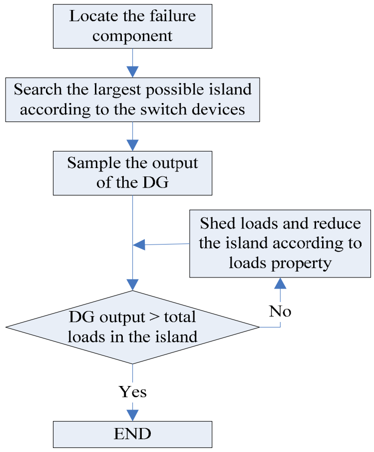

Fig. 2.Island Strategy Flow Chart

Table 1. The Outage Table of Wind-based DG

State	Power (MW.h/yr)	Cumulative Probability
0	1.0	1.000000
1	0.8	0.782278
2	0.6	0.693846
3	0.4	0.583651
4	0.2	0.454739
5	0.0	0.316633

Then, using the method proposed by [1], the DG outage table is formed as Table 1. Set rated power of the DG to be 1MW, and the multi-state model to be a 6 states model. When applying Monte Carlo simulation, the state of the DG is determined by comparing a random number and the cumulative probability in the outage table. By studying the cumulative probability, the uncertainty of power output of DGs (<10MW) could decrease the system's reliability under the island operation mode seriously. As a result, the installations of DGs are normally accompanied by storage devices such as pumped storage or battery-based storage.

3. Islanding Schemes

Island is a new operation mode brought by DGs in the distribution system, which is normally defined as a state that DGs providing energy to the customers independently. This part of the paper proposes a flexible islanding scheme according to the important level of the customers and the DG power output in order to minimum the total loss cause by system failures.

3.1. Steps of islanding

When system failure occurs, island operation mode allows isolating the failure by forming an island

and maintaining the DG in operation state, thus reducing the total load loss area and promoting system reliability. Before transferring to island operation mode, certain rules for islanding schemes should be established in advance. Fig. 2 is a flow chart of an islanding scheme.

3.2. Load-shedding strategy

Strictly speaking, load-shedding strategy is a rigorous mathematical optimization problem, which involves customer important level and economical loss evaluation. This paper provides a load-shedding strategy based on several constraints as follows:

- The distribution system topology and device configuration constraints

When system failure occurs, the possible islanding schemes are directly limited by the topology and device configuration of the distribution system. This paper breaks the distribution system into several regions to simplify the process, according to the installation of circuit breakers.

- Constraint of load level

According to the power system customer level classification, all customers are categorized into 3 levels based on the economic and political losses. In the process of load-shedding, top level customers such as hospitals are the last to shed when the output of DGs cannot meet the need of all the loads in the island.

- Minimum the loss of loads and customer number in the islanding schemes

On the bases of load level classification, the load-shedding schemes must minimum the total load loss and reduce the affected customer number.

In this paper, when the power provided by DGs does not meet the need of the total loads in the island, a load point is the smallest unit in the load-shedding strategy, which is different from power transmission system where load shedding is continuous in each load point. Since a load points in the distribution system only have two states (being removed from the island or stayed in the island), the original optimization problem has been simplified into a zero-one programming problem.

4. Monte Carlo Simulation

The application of Monte Carlo method in the distribution system simulation is described in this section.

Reference [5] proposed a combination of minimal path method and equivalent method for complicated distribution system reliability assessment. On one hand, in a distribution system where large amount of DGs are plugged in, the minimal path for one load point is no longer fixed and unique. As a result, the original minimal path method should be modified in order to evaluate the reliability of multi-power-resources systems. On the other hand, analytical methods suffer great complexity dealing with situations that multi-accidents happen at the same time. This paper chooses Monte Carlo method to calculate the reliability of distribution system with DGs, which also consider the possibility of more than one accident happening at the same time.

The first step of Monte Carlo stimulation is sampling the running state of every single component in the distribution system, which including DGs, lines and transformers.

For any component in the system i, the forced outage rate is f_i; X_i stands for one of its operation state. Let R be a uniformly distributed random number, and $R \in (0,1)$, thus:

$$X_i = \begin{cases} 1 & 0 \le R \le f_i \quad \text{component failure} \\ 0 & R > f_i \quad \text{component normal} \end{cases} \tag{2}$$

$P(X_i)$ is the probability function of X_i :

$$P(X_i - x_i) = \begin{cases} f_i & x_i = 1 \quad \text{component failure} \\ 1 - f_i & x_i = 0 \quad \text{component normal} \end{cases} \tag{3}$$

$X = (X_1, X_2, \cdots, X_m)$ stands for a state vector of a system. $x = (x_1, x_2, \cdots, x_m)$ is the value of the vector. When $X = 0$, the system is normal, otherwise the system is in a fault state. The joint probability distribution function of every component in the system could be calculated based on forced outage rate of each component and their relationships.

After the sampling process, the system status is determined. If the system is in a fault state, the result of the system failure should be evaluated. The total load loss, outage time and other reliability indexes are estimated through system failure consequences assessment.

5. Failure Consequence Assessment

This paper proposes a new method to evaluate the failure consequences of the distribution system after Monte Carlo sampling, which is based on the concept of zoning and minimal path method.

The concept of zoning is meant to break the complex distribution system with DGs into several small regions, according to the circuit breaker configuration in the system. Therefore, the failure consequence assessment could be separated into two levels: inter-regional assessment and within-regional assessment.

The concrete steps go as follows:

- **Step 1:** Zone the distribution system into several regions. There are two kinds of switches in the system: automatic switches and manual switches. The system is zoned, according to certain automatic switches such as circuit breakers. See Fig. 3.
- **Step 2:** Search the inter-region minimal path for each region. Table 2 shows how to search the minimal path set for each region. Note: The elements in the minimal path set are also regions.

Table 2. Zoning Result

Region	Minimal Path set elements
Region No.1	None
Region No.2	Region No.1
Region No.3	Region No.1
Region No.4	Region No.1, Region No.3
Region No.5	Region No.1, Region No.3

- **Step 3:** Category the devices in each region into two types: main feeder devices and branch feeder devices.
- **Step 4:** When the system is in a failure state, each region in the system could be categorized into several states, which presents the inter-regional relation: 1) Accident happens on the device on the main feeder in the studied region. 2) Accident happens on the device on the branch feeder in the studied region. 3) Accident happens on devices on the main feeder outside the studied region, but the fault region is an element of the minimal path set of the studied region.
- **Step 5:** The final consequences assessment could be studied within each region independently, for the reason that inter-regional influences have been considered when categorizing each region into 3 states above. (Assuming all branch feeders are equipped with fuses and disconnecting switches)

State 1: The failure device is on the main feeder in the region.

a) Region without DG: Every customer in the region suffers an interruption. The interruption duration of customers upstream the fault device is fault isolating time, while the interruption duration of other customers is fault device repairing time.

b) Region with DG: Every customer in the region suffers an interruption.

If the fault device is on the upstream side of DGs, the interruption duration of customers in the island or on the upstream side of the fault device is fault isolating time, while the interruption duration of other customers is fault device repairing time.

If the fault device is on the downstream side of the DGs, the DGs have no influences on customers' interruption duration.

State 2: The fault device is on the branch feeder in the region. Only customers connected to the very branch feeder suffer an interruption and the interruption duration is the fault device repairing time, if there is no backup device.

State 3: The fault device is on main feeder in the minimal path region.

a) Region without DGs: Every customer in the region suffers an interruption, and the interruption time is the fault device repairing time.

b) Region with DGs: Every customer in the region suffers an interruption. After applying the islanding strategy, the interruption duration of customers in the island is fault isolating time, while the interruption duration of customers outside the island is fault device repairing time.

This is the method for failure consequence assessment of the distribution system after the system operation state has been determined by Monte Carlo simulation. The benefits of this approach lies in that it breaks the complex system into several regions and allows evaluating the consequence of the fault state in unit of every region, which is much easier than evaluating the distribution system fault state consequence as a whole.

6. Multiple Accidents and Switch Configuration

During the process of reliability assessment, multiple accidents are considered using superposition method. Assuming two components Let A and B be in failure state simultaneously in the system after sampling.

When sampling is over, the fault consequence assessment of two fault components (A and B) could be dealt with separately and then combine the result of two single-fault consequence assessments into a multiple-fault consequence assessment following certain rules.

Step 1: Evaluate the load losses and various customer reliability indexes of two single-fault states arouse by component failure A or B separately.

Step 2: Combine the reliability assessment result of two single-fault state into a multi-fault state result. Customers who suffer power supply interruption in the multi-fault state are the union of customers in the two single-fault state. The interruption duration of each interrupted customer in the multi-fault state is the longest duration of the two single-fault states.

If more than two components fall into fault state at the same time, similar superposition method could be applied.

With proper control strategy, the introduction of DGs to the distribution system could help improving the reliability. However, the improvement largely depends on the proper switch devices configuration of the system. The circuit breakers are the only devices that can interrupt a short-circuit current, so the variety of islanding schemes is constraint by the installation of circuit breakers in the system, which is studied in detail in the example below.

7. Analysis of Example

The feeder line 4 in IEEE RBTS Bus6 [7] is adopted as an example to illustrate the application of Monte Carlo method in reliability assessment of distribution system with DGs. Two DGs are installed separately on line 56 and line 64. Assuming transformers have backups and DGs installation is accompanied with storage devices. In order to manifest the improvement of reliability brought by DGs, the disconnect switch on line 45 has been changed into a circuit breaker, and other changes in switch configuration are shown in Fig. 3. Table 3 classified all the loads in the Fig. 3 into 3 different load levels.

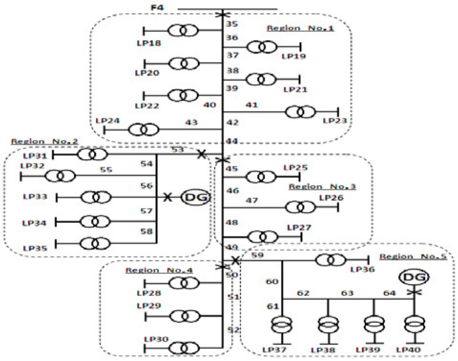

Fig. 3.IEEE RBTS Bus6 Feeder F4

Table 3. Customer Level Classification

Customer Level	Customer
Level 1	21 22 25
Level 2	18 19 20 23 32 34 37
Level 3	24 26 27 28 29 30 31 33 35 36 38 39 40

Through C++ programing, the paper studied the differences in reliability brought by the introduction of DGs, considering the case of multiple accidents. During the Monte Carlo simulation, set the sampling times to be 10^6 times. The reliability improvement brought by DGs could be concluded by comparison between the customer reliability data in Table 4 and Table 5. Table 6 shows the system reliability changes between system with and without DGs. Although the probability of multiple faults is very low, Table 7 shows the system reliability deteriorates when considers multiple fault conditions. Since switch device configuration could affect the reliability of the system greatly, Table 8 shows the reliability of customers improved greatly on an extreme condition that all disconnect switches on feeders are replaced by circuit breakers in Region No.5 and No.2.

Table 4. Customer Reliability Data (System without DGs)

Customer	Interruptions	EENS (MW.h/yr)	Customer	Interruptions	EENS (MWh/yr)
18	899	1.3065	30	2150	4.7104
19	909	1.4134	31	1817	2.4735
20	904	1.9806	32	1879	3.1751
21	903	2.0828	33	1822	2.5298
22	902	1.6356	34	1827	4.0027
23	959	1.3937	35	1817	4.1909
24	979	2.6217	36	2506	3.4114
25	1626	2.2135	37	2555	4.3175
26	1688	4.1862	38	2491	6.1776
27	1614	2.2410	39	2500	3.4712
28	2158	2.9377	40	2495	6.6814
29	2157	2.9949			

Table 5. Customer Reliability Data (System with DGs)

Customer	Interruptions	EENS (MW.h/yr)	Customer	Interruptions	EENS (MWh/yr)
18	890	1.2934	30	2129	4.6644
19	888	1.3808	31	1821	2.4789
20	888	1.9455	32	1885	3.1853
21	895	2.0643	33	1825	2.5339
22	888	1.6102	34	1813	3.9721
23	936	1.3603	35	1820	4.1978
24	927	2.4824	36	2447	3.3311
25	1627	2.2012	37	2488	4.2042
26	1687	4.1836	38	2447	6.0685
27	1615	2.2424	39	2432	3.3767
28	2130	2.8996	40	2443	6.5422
29	2136	2.9658			

Table 6. System Reliable Index Comparison

System Configuration	EENS (MW.h/yr)	ASAI
without DGs	71.3621	0.999573
With DGs	72.1489	0.999657

Table 7. Multiple Faults

Reliable Index	Consider multiple faults	Not consider multiple faults
EENS (WM.h/yr)	72.1489	71.3621
ASAI	0.999568	0.99957
Multiple Faults Times	19	0

Table 8: Customer Reliability Data (Partial Data)

Customer	Interruptions	EENS (MW.h/yr)	Customer	Interruptions	EENS (MWh/yr)
32	435	0.7351	37	425	0.7182
34	712	1.5599	39	898	1.2468
36	544	0.7405	40	579	1.5505

8. Conclusion

Monte Carlo simulation has many advantages in distribution system reliability assessment, which is more obvious when DGs are widely introduced to the distribution system. Firstly, Monte Carlo simulation avoids the various operation issues brought by DGs. Moreover, Monte Carlo simulation can better describe the uncertain properties of DGs. It is also much easier to discuss multiple accidents when applying Monte Carlo simulation.

The reliability can be improved when DGs and proper islanding schemes are introduced to the distribution system. The example also illustrates that the switch device configuration plays a critical role in deciding how much the improvement could be, which calls for a balance between switch device investment and system reliability.

The multiple accidents discussion in this paper does not incorporate the potential relation between multiple accidents and islanding schemes, which needs further study. And the reliability calculation results in the example are based on the non-sequence Monte Carlo method, thus accurate frequency indexes are unavailable. As the reliability assessment of distribution system with DGs is a relatively new research area and involves many issues such as DG models, switch device configuration, islanding schemes, and multiple accidents assessment and control system, the example in this paper cannot cover every aspect in the practical application.

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References

[1] Shuyun ZHU. "Studies on Reliability Evaluation of Large Wind Farm Integration into Power System," M.S. thesis, Xi'an Jiaotong University, China, May 2008.

[2] Mahmud Fotuhi-Firuzabad, Abbas Rajabi-Ghahnavie, "An Analytical Method to Consider DG Impacts on Distribution System Reliability," [C]. IEEE Transmission and Distribution Conference, 2005.

[3] Chuanshuan LIU. "Distribution Network Reliability Considering Distribution Generation," Automation of Electric Power System. [J], Vol. 31, No.22 Nov. 25, 2007.

[4] Jing ZHANG. "Research on the Model for Distribution Network Reliability Evaluation Based on Sequential Monte-Carol Simulation," M.S. thesis, HeFei University of Technology, China, Mar 2004

[5] Zhaohong BIE. "Reliability Evaluation of Complicated Distribution Systems," Journal of Xi'an Jiaotong University. [J], Vol. 34, No.8, Aug. 2000.

[6] BOLLEN M H J, SUN Y, AULT G W, "Reliability of distribution networks with DER including intentional islanding," [C], International Conference on Future Power Systems. Amsterdam, Holland: [s.n.], 2005; 6.

[7] Roy Billinton, Satish Jonnavithula. "A Test System For Teaching Overall Power System Reliability Assessment," IEEE Transaction on Power Systems. [J], Vol. 11, No.4, November 1996.