MATEC Web of Conferences **55**, 03008 (2016) DOI: 10.1051/matecconf/20165503008
ACPEE 2016

Reliability Evaluation of Distribution System Considering Sequential Characteristics of Distributed Generation

Wanxing Sheng[1], Xiaoli Meng[1], Tingting Fan[2] and Songhuai Du[2,a]

[1]*China Electric Power Research Institute, Power Distribution Department, 100192, Beijing*
[2]*China Agricultural University, College of Information and Electrical Engineering, 100083, Beijing*

Abstract. In allusion to the randomness of output power of distributed generation (DG), a reliability evaluation model based on sequential Monte Carlo simulation (SMCS) for distribution system with DG is proposed. Operating states of the distribution system can be sampled by SMCS in chronological order thus the corresponding output power of DG can be generated. The proposed method has been tested on feeder F4 of IEEE-RBTS Bus 6. The results show that reliability evaluation of distribution system considering the uncertainty of output power of DG can be effectively implemented by SMCS.

1 Introduction

With the development of social economy, the requirement of power quality and reliability becomes higher and higher. Distribution network is connected directly with consumers, and it has great impact on the reliability of power supply[1-3]. Through analyzing the reliability level of distribution system, reliability evaluation can help find weaknesses in the system and put forward effective improvement measures.

Distributed generations have greatly increase the complexity of reliability analysis of distribution network. Some investigations have been made. In [4], the operating characteristics and reliability of DG operated in isolated island mode based on interval analysis had been proposed. With the consideration of the stochastic characteristics of power output of photovoltaic generation and wind power generation, a reliability evaluation algorithm for distribution network containing micro-grid had been investigated in [5]. The formation probability of isolated island had been computed based on analytical method in [6-7].

This paper describes a method to identify the faults' effect on load points' reliability index based on equivalent simplification of distribution network. The partition simplification approach can simplify the process of fault analysis and improve the calculation efficiency. According to the randomness of output power of DG and the time series characteristic of load, a reliability evaluation model based on sequential Monte Carlo simulation for distribution system is established. Then the algorithm process based on sequential simulation method is proposed to make the reliability evaluation of feeder F4 of IEEE-RBTS Bus 6.

[a] Corresponding author : songhuaidu@cau.edu.cn

DOI: 10.1051/matecconf/20165503008

2 Complex Distribution Network Reliability Evaluation

2.1 Reliability Indices of Distribution System

The reliability level of one distribution system can be evaluated from two aspects. One is consumer level, another is system level. Two frequently used reliability indices for users of load points are as follows. Fault rate λ_i (number of outages/year) and annual outage duration U_i (sum of the outages time/year).

The reliability level of the system is evaluated according to the outage frequency and the average outage time of load points. The commonly used indices are system average interruption frequency index (SAIFI) and system average power interruption duration index (SAIDI). Their respective formula is expressed as:

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{1}$$

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \tag{2}$$

where λ_i, N_i and U_i stand for fault rate, total number of users and annual average outage duration of load point *i*, respectively.

2.2 Partitions of Distribution System

Distribution system reliability is not only related to network topology as well as switch configuration which decides the range of failure influence and power supply recovery. The process can be divided into two phases after fault occurred in distribution network: fault isolation and fault recovery. In fault isolation stage, quick removal of failure is completed by circuit breaker; in fault recovery stage, sectionalizers isolate fault and circuit breaker close in order to restore the power supply for blackout zone which is non-fault. Therefore, the switches can be seen as boundaries which can divide the whole network into several region units which can be defined as feeder line areas. The components belonging to the same region have the same fault effect on load points. Similarly, the load points located in the same region are under the same influence of any fault. Therefore, they have the same failure rate and the same outage duration and can be equivalent to one load point. The partition approach can simplify the process of fault analysis and improve the calculation efficiency.

A feeder line area does not contain switches and it is the smallest analysis unit of fault. Equivalent reliability parameters of feeder line area can be calculated as follows:

$$f_{el} = \sum_{i=1}^{N_{el}} f_i \tag{3}$$

$$t_{el} = \sum_{i=1}^{N_{el}} f_i t_i \Big/ f_{el} \tag{4}$$

where f_{el} and t_{el} are the equivalent failure rate and equivalent repair time of feeder line area *l*; f_i and t_i are the failure rate and repair time of component *i*; N_{el} is the number of components in feeder line area *l*.

2.3 Area Classification for Distribution Network with DGs based on Fault Effect

When a specific failure occurs in distribution system, areas of different locations will be affected by different degrees. Therefore, corresponding to the fault occurred, areas in distribution system can be divided into the following categories:

(1) Fault area

The area where the failed component located is defined as fault area. The outage time for load points in fault area will be the repair time of feeder line area.

(2) No-effect area

Load points in this area will not be affected by failure, so there is no power outage.

(3) Isolate area

The area is located in the upper reaches of the fault and it can be connected with primary substation after the fault is isolated. Another case is that the area is located in the lower reaches of the fault and load can be transferred to other line by loop switches. The outage time for load points in isolate area will be the switching time of sectionalizer.

(4) Island area

When fault occurs, if there is a switch installed between the fault and some DGs, the area downstream the switch may operate in island mode. Whether the load points are outage or not depends on the ability of DG supply to load demand in island [8].

3 Reliability Assessment Model for Distribution System

3.1 Distribution Network Components Modelling

The main components of distribution network, such as feeders, transformers, circuit breakers and sectionalizers can be seen as repairable components. Their reliability parameters are failure rate (λ) and repair rate (μ). It is assumed that the time to failure (*TTF*) and the time to repair (*TTR*) obey exponential distribution.

Taking *TTF* for example, the probability density function is:

$$f(t) = \lambda e^{-\lambda t} \tag{5}$$

where $f(t)$ representsthe probability of failure of components in the time of t, its distribution function is:

$$F(t) = 1 - e^{-\lambda t} = \delta \tag{6}$$

$F(t)$ represents the probability of the components work properly until time is t, and δ is a random number between 0 and 1.The *TTF* of components can be obtained based on the following equations:

$$TTF = -ln\delta/\lambda \tag{7}$$

Through Monte Carlo sampling to simulate the evaluation and fault status of components, then to simulate the entire distribution system operation condition.

3.2 Distributed generation modelling

3.2.1 Diesel generator

Traditional distributed generation is not affected by the factors of natural environment and its output can be controlled at a constant value. Therefore, traditional distributed generation can be represented by constant power model. Availability rate ρ_A is used to reflect generating units' performance [9].

3.2.2 Wind turbine

It is assumed that the wind speed of each hour obeys two parameter Weibull distribution. Its **c**umulative probability density function is:

$$F(v) = p(x < v) = 1 - \exp\left[-\left(\frac{v}{c} \right)^k \right] \tag{8}$$

The parameters k and c can be calculated by parametric estimation according to historical data [10-11]:

$$k = \left(\frac{\sigma}{v_m} \right)^{-1.086} \tag{9}$$

$$c = \frac{v_m}{\Gamma(1 + 1/k)} \tag{10}$$

where v_{m} and σ is respectively the mean value and variance of wind speed.
In the Monte Carlo simulation, Weibull distributed random number can be generated by inverse transformation:

$$v = c[-\ln(1-R)]^{1/k} = c[-\ln(R)]^{1/k} \tag{11}$$

The output power of a wind turbine is dependent on the wind speed as well as the parameters of the power performance curve. Therefore, once the Weibull parameters k and c were got, the output power can be calculated as follows [12]:

$$P(v) = \begin{cases} 0 & (0 \le v \le v_i) \\ P_r * \dfrac{(v - v_i)}{(v_r - v_i)} & (v_i \le v \le v_r) \\ P_r & (v_r \le v \le v_o) \\ 0 & (v_o \le v) \end{cases} \tag{12}$$

where v_{i}, v_{r} and v_{o} are the cut-in speed, rated speed and cut off speed of the wind turbine, respectively. P_{r} is the rated output power of the wind turbine.

3.3 Load Modelling

The load will be assumed to be constant during an hour and changes discretely for every hour. The load value is determined from the sequential load data of IEEE-RTS 79 reliability test system. The system provides weekly peak load as a percentage of annual peak load; daily peak load cycle as a percentage of the weekly peak load; and hourly peak load as a percentage of the daily peak load.

4 Sequential Simulation Process of Reliability Evaluation

When analysing reliability of distribution system including DGs, two different operating modes should be taken into consideration. Through the above analysis, the reliability evaluation algorithm processes was proposed based on sequential Monte Carlo simulation.

(1) Data initialization. Determine the simulation time and initialize the system. Set $t = 0$.

(2) Simplify system and divide it into several partitions according to topological structure.

(3) Determine the number of partitions and randomly generate the same account of random numbers δ_1, $\delta_2 \ldots \delta_{\mathrm{n}}$. Calculate *TTF* of each area according to the random numbers: $TTF = -ln\delta / \lambda$.

(4) Select the area that has the minimum *TTF* as the fault area. Treat *TTF* as the minimum working time of system and add up simulation time. Set $t = TTF + t$.

(5) After sampling to get the fault area, calculate the repair time of it. Choose the equivalent repair time as its *TTR*.

(6) According to the fault that occurs, analyse the fault effect types of load points respectively. The load points are divided into four categories: ① load points in fault area; ② load points in no-effect area; ③ load points in isolate area; ④ load points in island area.

(7) For the first type, load points will not be outage; for the second type and third type, add up the outage duration and the number of blackouts of load points respectively. Treat the fourth type as follows:

① Calculate the total output power of DGs $P_{DG}(t)$ and the total power of load demand $P_L(t)$ within island in the time of t.

② Determine whether or not it meet that: $P_{DG}(t) >= P_L(t)$. If it meets the condition, load points will not be outage; if not, record the blackout and add up the outage duration of load points in island.

③ Determine whether or not t equals to the time when fault recovery has been completed. If so, output the fault records of load points and go to the next step; if not, set $t = t+1$ and go to step ①.

(8) Determine whether or not the present time t achieves the desired simulation Years. If so, go to the next step; if not, go to step (3) and continue to simulation.

(9) Calculate the failure rate and annual average outage duration of each load point according to the recorded data.

(10) Calculate the reliability of overall system according to load points' index.

The above algorithm process is shown in Figure 1.

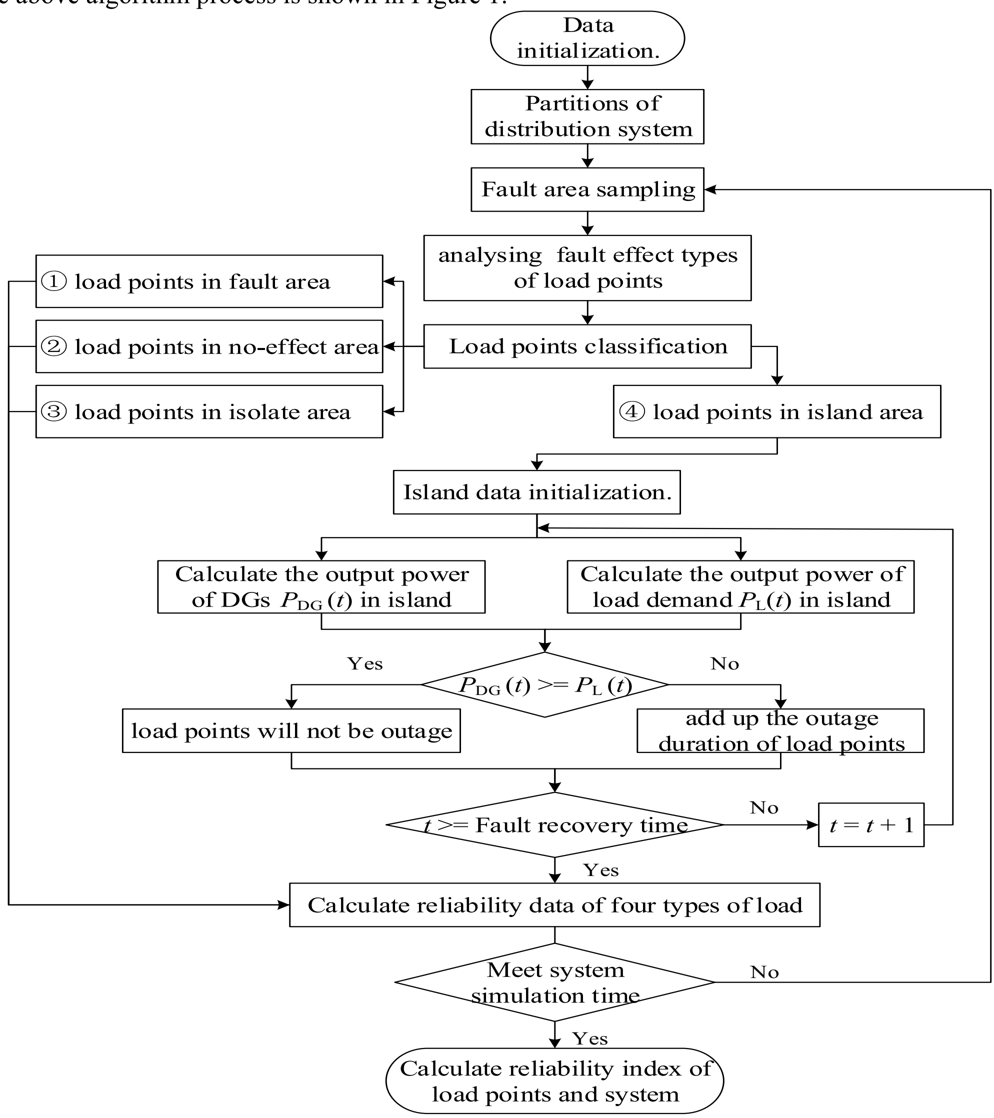

Figure 1. Flow chart of reliability evaluation

5 Case Study

The paper has analysed reliability of feeder F4 of IEEE RBTS-BUS6 network, which is shown in Figure 2. Renewable distributed generations are integrated to feeder 19 and feeder 25, which constitute island 1 and island 2. The peak load of island 1 and island 2 are 2.4 MW and 2.6 MW. Wind power and photovoltaic power generation operate in parallel with grid. Diesel generating sets are running as standby. Cut in, rated and cut out speed of wind turbine are respectively 4, 15 and 25 m/s. The mean value and variance of wind speed are respectively 7 and 13.4. It is assumed that there are only circuit breakers and sectionalizers in the feeder which are completely reliable. The parameters of lines can be found in the references [13-14]. The availability rate of DG is 0.95 and conversion time is 0.1 h [9]. The operation time for sectionalizer is 2 h.

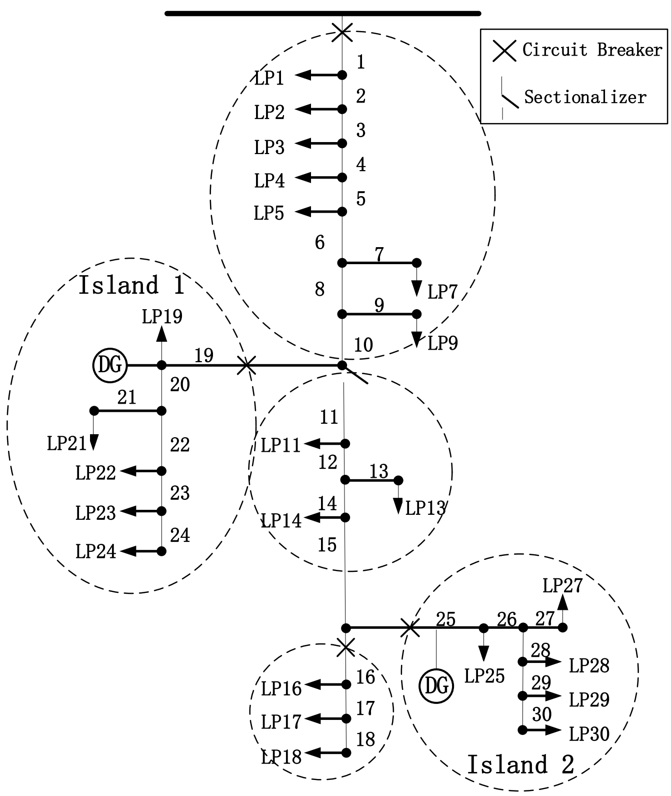

Figure 2. Test system

According to the proposed partition method in this paper to simplify the test system, as shown in Figure 2, it can be seen that branches 1-10 belong to region 1 and branches 11-15 belong to region 11, branches 16-18 belongs to region 16, branches 19-24 belong to region 19, branches 25-30 belong to region 25. The load points are numbered according to a certain sequence number, and the corresponding numbers of the upstream branch feeders are used to name.

According to the flow chart of algorithm proposed in this paper to carry out reliability evaluation of distribution system containing distributed generation:

Scenario 1: No distributed generation is contained in distribution system. Analysis method and Monte Carlo method were used to calculate reliability of system respectively.

Scenario 2: Distributed generation is installed in island 1. The capacity of distributed power supply is 1.15 times the load demand in island 1. Among them, the capacity of diesel engine accounts for

50% of total power generation capacity. Analysis method and Monte Carlo method were used respectively.

Scenario 3: Distributed generation is installed in island 2. The capacity of distributed power supply is 1.15 times the load demand in island 2. Among them, the capacity of diesel engine accounts for 50% of total power generation capacity. Analysis method and Monte Carlo method were used respectively.

In the above scenarios, the reliability indices of 5 typical load points and system reliability indices, as shown in Table 1-Table 3.

Table 1. Failure rates for typical load points

Scenario		LP 1	LP 11	LP 16	LP 19	LP 25
1	Analytical method	1.2569	1.2557	1.6491	1.9006	1.8872
	SMCS	1.2569	1.2569	1.6488	1.9006	1.8870
2	Analytical method	1.2569	1.2557	1.6491	1.9006	1.8872
	SMCS	1.2569	1.2569	1.6488	1.9006	1.8870
3	Analytical method	1.2569	1.2557	1.6491	1.9006	1.8872
	SMCS	1.2569	1.2569	1.6488	1.9006	1.8870

Table 2. Annual average outage duration for typical load points

Scenario		LP 1	LP 11	LP 16	LP 19	LP 25
1	Analytical method	6.8622	10.0547	13.1911	12.0168	15.0959
	SMCS	6.8616	10.0550	13.1906	12.0177	15.0962
2	Analytical method	6.8622	10.0547	13.1911	6.3884	15.0959
	SMCS	6.8616	10.0550	13.1906	6.3885	15.0962
3	Analytical method	6.8622	10.0547	13.1911	12.0168	6.7002
	SMCS	6.8616	10.0550	13.1906	12.0177	6.7004

Table 3. System reliability indices

Scenario		SAIFI	SAIDI
1	Analytical method	1.4785	9.9048
	SMCS	1.4787	9.9048
2	Analytical method	1.4785	9.0539
	SMCS	1.4787	9.0539
3	Analytical method	1.4785	8.7836
	SMCS	1.4787	8.7836

According to the data of three scenarios, it can be seen that the results of Monte Carlo method are very close to the results of analytical method. In addition, it can be seen from table 2, the failure rate of load point 19 and 25 is higher, which belong to relatively weak part in system. Therefore, distributed generation is connected to feeder line area 19 and feeder line area 25 respectively in scenario 2 and scenario 3.

Compare reliability assessment results of scenario 2, 3 with scenario 1, it can be seen that when distributed generation access to distribution system, the reliability indicators of load points which are out of the island do not change, however, the annual outage time of load points that are in the island has been significantly improved. Reliability of the whole system has also improved. The reason for this is that, when the primary grid fails, if distributed generation output is greater than load demand in island, the load points' interruption duration only equals to the start time of distributed generation, which is far less than fault repair and isolation time.

The reliability assessment results of scenario 2 and scenario 3 show that, when distributed generation is connected to the island 2, the reliability level of system is better than that distributed generation connected to island 1. The main reason is that, island 2 is in the feeder terminal, which is far from the superior substation. When there is no distributed power in island 2, load points will be outage until the fault is repaired. However, the fault interruption duration of load points in island 1 may be the fault repair time or isolation time. Therefore, distributed power installed far from the location of primary substation can improve the reliability of the whole system better.

6 Conclusions

Considering the randomness of distributed generation output power and the sequential characteristic of load, the reliability evaluation model based on Monte Carlo simulation for distribution system is established. In the case study, the application of the proposed method has been verified on the feeder F4 of IEEE RBTS-BUS6. The results show that reliability evaluation of distribution system considering the uncertainty of DG and load can be effectively implemented by SMCS and islanding operation can positively improve the reliability of distribution network.

References

1. R. Billinton, R.N. Allan, "Reliability Evaluation of Power Systems", New York: Premium Press, **14**(1), pp. 51-57, (1996).
2. W. Huang, C.H. Sun, Z.P. Wu, "A Review on Microgrid Technology Containing Distributed Generation System", *Power System Technology*, **33**(9), pp. 14-18, (2009).
3. L.Y. Kang, H.X. Guo, J. Wu, "Characteristics of Distributed Generation System and Related Research Issues Caused by Connecting It to Power System", *Power System Technology*, **34**(11), pp. 43-47, (2010).
4. Y. Sun, M. Bollen, G. Ault, "Reliability Analysis of Islanded Distribution Systems with Distributed Energy Resources", *Power System Technology*, **32**(23), pp. 77-81, (2013).
5. X.D. Wang, J.K. Lin, "Reliability Evaluation Based on Network Simplification for the Distribution System with Distributed Generation", *Automation of Electric Power Systems*, **34**(4), pp. 38-43, (2010).
6. Y.M. Atwa, E.F. El-Saadany, A. Guise, "Supply Adequacy Assessment of Distribution System Including Wind-based DG during Different Modes of Operation", *IEEE Trans on Power Systems*, **19**(25), pp. 78-86, (2011).
7. M. Atwa, E.F. E1-Saadany, M.A. Salama, "Adequacy Evaluation of Distribution System Including Wind/Solar DG during Different Modes of Operation", *IEEE Trans on Power Systems*, **4**(26), pp. 1945-1952, (2011).
8. G. Zini, C. Mangeant, J. Merten, "Reliability of Large-scale Grid-connected Photovoltaic System", *Renewable Energy*, **7**(36), pp. 1670-1676, (2011).
9. S. Conti, R. Nicolosi, S. A. Rizzo, "Generalized Systematic Approach to Assess Distribution

System Reliability with Renewable Distributed Generators and Microgrids", *IEEE Trans. Power Delivery*, **27**, pp. 261-270, (2012).
10. M. Al-Muhaini, G. T. Heydt, A. Huynh, "The Reliability of Power Distribution Systems as Calculated Using System Theoretic Concepts", *IEEE Power Energy Society General Meeting*, pp, 1-8, (2010).
11. X. Xie, Y. Yuan, W.Z. Zou, "Reliability Evaluation of Microgrid Power Supply in Emergency Non-scheduled Isolated Mode", *Automation of Electric Power Systems*. **36**(9), pp. 8-22, (2012).
12. Y. Xu, Y.C. Wu, "Reliability Evaluation for Distribution System Connected with Wind-turbine Generators", *Power System Technology*, **35**(4), pp. 154-158, (2011).
13. Y. M. Atwa, E. F. El-Saadany, M. M. A. Salama, R. Seethapathy, M. Essam, and S. Conti, "Adequacy evaluation of distribution system including wind/solar DG during different modes of operation", *IEEE Trans. Power System.*, **26**(4), pp. 1945–1952, (2011).
14. R.N. Allan, R. Billinton, I. Sjarief, "A Reliability Test System for Educational Purposes: Basic Distribution System Data and Results", *IEEE Trans on Power Systems*, **6**(2), pp.813-820, (1991).
15. R. Billinton, S. Johnnavithula, "A Test System for Teaching Overall Power System Reliability Assessment", *IEEE Trans on Power System*, **11**(4), pp.1670-1676, (1996).