

Impact of Distributed Generation on Electric Power Distribution System Reliability

“Application of IEEE Std 1366 and IEEE Std 1547”

Shiyu Liu, Yue Yuan

School of Energy and Electrical Engineering, Hohai University, Nanjing, P. R. China, 211100

E-mail: liushiyu982@gmail.com

Abstract--With the development of the smart grid, more and more distributed generations (DGs) are introduced to the distribution networks, which affect the power system obviously. To begin with, this paper proposes a multi-state model for DGs. Then a sequential Monte Carlo simulation with minimal path method is discussed. In addition, referring to IEEE Std 1547 and combining island schemes, each load point and reliability indices defined in IEEE Std 1366 are estimated to discuss the reliability of the system with DGs. Finally, an example based on IEEE RBTS Bus6 is applied to test the method, validating that the DGs access can improve the distribution system reliability.

Index terms—reliability, distributed generation, minimal path, Monte Carlo method

I. INTRODUCTION

In recent years, as a very important part of the smart grid, distributed generations (DGs) with its abundant energy resources and environmental friendly operation are enjoying popularity in the distribution system. DGs, which are defined as generations with the capacity of less than 10 MW, are widely introduced to the present power distribution system. Although these distributed energy resources have many advantages such as low investment, environmental friendliness and high flexibility, they also changed the structure of the traditional distribution system and brought many uncertainties to the present system [1].

Integration of DGs totally changes the radial topology features of the traditional distribution systems. In addition to uncertainty of DG's output, the power flow direction in distribution networks with DGs is changed with the operation state of networks, namely, bidirectional power flow, which brings uncertainty of operating condition of distribution networks. Also, frequency offset and voltage fluctuations are challenges to the power quality and reliability of distribution system. All above make essential changes in steady state and dynamic characteristics of distribution networks with DGs.

Therefore, there is a great change in the theory and calculation method for the reliability evaluation of the new distribution systems with DGs.

Firstly, as DGs, depending on energy resources such as wind and PV, are random, traditional generation model could not be applied for DG directly. Secondly, when the system failure occurs, island operation mode allows isolating the failure by forming an island and maintaining the DG in operation state. However, factors such as uncertainty of the distribution generation output power, load uncertainty and switch configuration are supposed to be considered in islanding schemes. Based on the points above, this paper proposes a multi-state model to meet the properties for DGs. Considering the influence of the distributed power supply of the distribution system reliability, the sequential Monte Carlo simulation method is used to evaluate the system reliability based on the minimal path of the DG. The reliability indices defined in IEEE Std 1366 [2] are utilized to give a reference to the quantitative assessment of the reliability benefit brought by DG. Meanwhile, IEEE Std 1547 [3] makes references for integration of DGs in distribution systems. Finally an example based on IEEE RBTS Bus6 is applied to test the presented method.

II. MODELING DG OUTPUT

Taking wind-based generation as an example, this part of paper proposes the multi-state model to model the DG's output.

Different kinds of DGs and its modeling could influence the reliability assessment of the system greatly. Due to features of DG itself, the traditional generation model cannot be applied to DG directly. To begin with, most DGs are less than 10MW, thus cannot be modeled as infinite power resources. What is more, the uncertainty of DG power output is related to the original resources it needs, thus DG cannot be modeled as traditional power unit, which is much more stable and easier to control. Finally considering all the characteristics of DGs, a multi-state model could meet the properties for most DGs when applying Monte Carlo simulation.

As a wind-based generation, the power and wind relation of N wind turbines refers to :

$$C_T(v) = \begin{cases} 0 & 0 \leq v \leq v_{ci} \\ a + bv & v_{ci} \leq v \leq v_r \\ R & v_r \leq v \leq v_{co} \\ 0 & v \geq v_{co} \end{cases} \quad (1)$$

where $C_T(v)$ 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[4], a , b are constants, where

$$\begin{cases} a = \frac{Rv_{ci}}{v_{ci} - v_{cr}} \\ b = \frac{R}{v_{cr} - v_{ci}} \end{cases}$$

Although Weibull wind speed distribution function fails to 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[5].

Fig. 1 shows the data of wind speed according to Weibull distribution during 8760 hours, where $c=10.0$ and $k=2.8$.

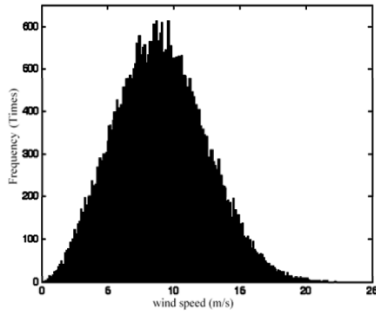


Fig. 1. Weibull Wind speed statistics by distribution

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

Subsequently the DG outage table is formed as Table 1 based on the method proposed by [5]. Set rated power of the DG to be 1MW, and the multi-state model to be a 6 states model. According to the cumulative probability in the outage table, DG output can be simulated in the sequential Monte Carlo simulation method.

III. MINIMAL PATH METHODS

The minimal path is the shortest path from power source to the load point, which can be formed in the search method. Search method is basically to search from input node of network to output node in sequence to find all the minimal paths. In this paper, the distribution system followed in Fig.2 is divided into 5 parts to simplify the process, according to the installation of circuit breakers.

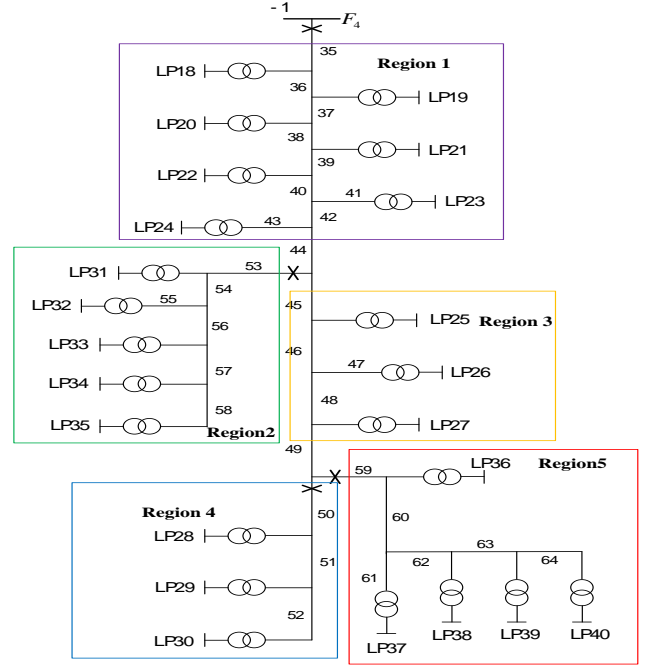


Fig.2 Minimal path map of F4 in IEEE RTBS-BUS6

When system failure occurs, island operation mode allows isolating the failure by forming an island and maintaining the DG in operation state, which improves reliability of load point in the island. However, due to the finite capacity of DG, load point outside the island cannot be supplied. Thus DG has an impact on the reliability index of load point inside the island.

This paper proposes improved minimal path method as follows. To begin with, after gaining the minimal path of each load point, all devices are classified into 2 types: devices on the path and not on the path.

a. Devices on the path:

- 1) If devices on the path in the range of islanding scheme, faults on these devices will cause load point outage. Therefore such devices should be in the calculation of reliability.
- 2) If devices on the path is out of the range of islanding scheme, together with sectioning like disconnecting switch in the main feeder, the outage time caused by faults is $\max\{S, T\}$ (S is operation time of sectioning; T is switching operation time when island forms). Therefore, outage time and outage rate of these

devices are involved in the reliability calculation.

b. Devices not on the path

- 1) When faults occur on the branch lines, the fuse works, which has no impact on other branches.
- 2) For the main feeder, the outage time of the front load point caused by devices behind the switch is the operation time S.

According to principles above, equivalent fault rate of load point and interruption duration are calculated. As a result, reliability index of distribution system with DG is calculated.

IV. APPLICATION OF IEEE Standards

a. Application of IEEE Std 1366

IEEE Std 1366™-2012[2] identifies quantitative distribution reliability indices, which are used in this paper to study the reliability impact of DG. Specifically, the following indices are used.

- SAIFI: System Average Interruption Frequency Index
 SAIDI: System Average Interruption Duration Index
 CAIDI: Customer Average Interruption Duration Index
 CAIFI: Customer Average Interruption Frequency Index

Besides, a well-acknowledged index, EENS, is used to represent the energy not served in a distribution system.

b. Application of IEEE Std 1547

IEEE Std1547, a series of technical standards, is the key standard for integration of micro-grids and distributed electric power resources [3].The configuration, design specification andoperation mode of micro-grids in IEEE 1547 are reviewed in favor of the standards formulation, planning and design of micro-grids, which makes references for islanding schemes and integration of DGs in this paper.

V. MONTE CARLOSIMULATIONS

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

A.Sequential Simulation modeling of components

For any reparable component in the system; Failure rate is λ ; Repair rate is μ . MTTF stands for mean time to failures, and MTTR stands for mean time to repair, thus:

$$\begin{cases} MTTF = 1/\lambda \\ MTTR = 1/\mu \end{cases} \quad (2)$$

λ, μ are two basic parameters used to simulate component duration and characteristics of state transition in the Monte Carlo Simulation. Fig.3 as follows shows characteristics of state transition, value of which is determined through statistics of long-time running life of component and random state.

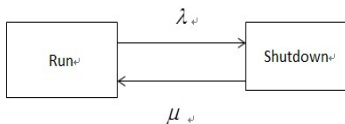


Fig.3 State transition diagram of components

Let m be no-failure operation time and r be maintenance time, both of which are random variables that obey the exponential distribution, thus:

$$\begin{cases} m = \frac{1}{\lambda} \ln \xi_1 \\ r = \frac{1}{\mu} \ln \xi_2 \end{cases} \quad (3)$$

ξ_1, ξ_2 are uniformly distributed random numbers, and $\xi_1, \xi_2 \in (0,1)$.

According to sampling theory as Equations (2) and (3) show above, a state vector of each component within a simulation time can be determined. Then a state vector of a system is determined on the basis of information of all components.

B. the Sequence Simulation Steps

For the distribution system including n_r feeders and n_z transformers, concrete steps of sequential simulation go as follows:

Step 1: Initialization

Initialize system clock $t_0=0$. All the feeders and transformers are in the normal operation condition in the original state. Initialize state counter $k=0$. Then simulate duration of each feeder and transformer in normal operation condition, getting time sequence $\{T_i\}_0, i=1, 2, \dots, n_r + n_z$. Thus duration of state 0 is $D_0 = \min\{T_i\}_0$;

Step 2: Consider the system state which is named k .

Make $k=k+1$, the system clock $t_k = t_{k-1} + D_{k-1}$. The new time sequence $\{T_i\}_k$ is determined based on the format as follows:

$$T_{i,k} = \begin{cases} T_{i,k-1} - D_{k-1} & T_{i,k-1} \neq D_{k-1} \\ \text{simulating to get the new state duration} & T_{i,k-1} = D_{k-1} \end{cases}$$

$T_{i,k-1}$ stands for the element of $\{T_i\}_{k-1}$; $T_{i,k}$ stands for the element of $\{T_i\}_k$. D_k stands for duration in state k , and $D_k = \min\{T_i\}_k$.

Judge the component state in the time $[t, t+D_k)$. If the component is in normal operation, go to step 4; otherwise to step 3.

Step 3:Search the fault component in the minimal path. Then plus one to the number of fault components and the path is in fault state. If load point is normal and all minimal paths are in fault state, the point will suffer an interruption. And the interruption time point starts as t_k .

Step 4:Search the restored component in the minimal path. Then subtract one to the number of fault components. If the number of fault components in the path is 0, it will be in operation state. If the load point suffers interruption and the minimal path is normal, then make it in operation state. And record the interruption duration.

Step 5:If it is in the simulation condition of convergence, stop sampling; otherwise, go to step2.

Step 6:Calculate reliability parameters of each load point and system.

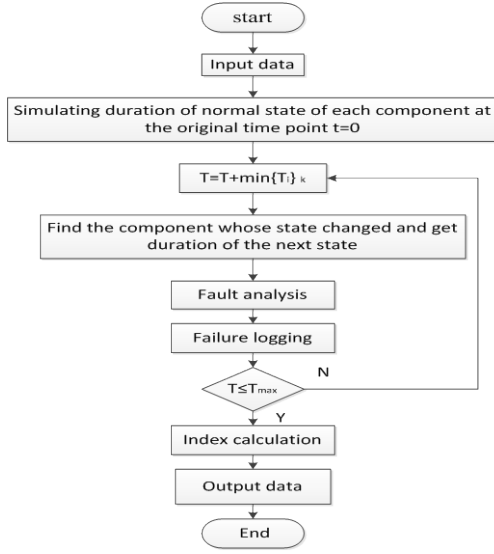


Fig.4 Flow chart for reliability evaluation of the distribution systems

VI. CASE STUDIES

The feeder line 4 in IEEE RBTS Bus6 as Fig.5 shows is adopted as an example to illustrate the application of Monte Carlo method in reliability assessment of distribution system with DGs, comparing with system without DGs.

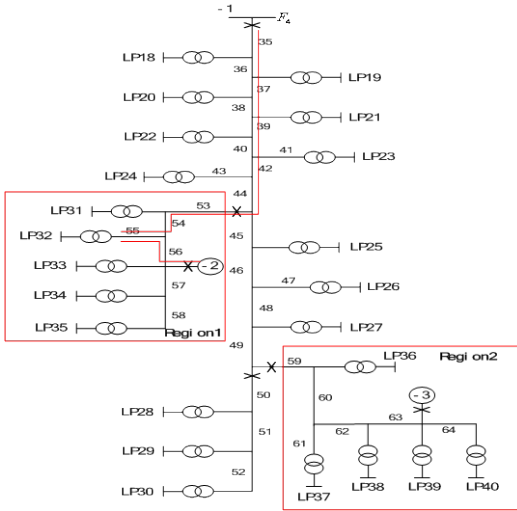


Fig.5 IEEE RBTS Bus6 Feeder F4

A. Consequence and Analysis of Distribution System without DGs

Assuming the simulation period is 1000 years, here are the reliability parameters:

For every 1km of the line, its FRA is 0.065 and MTTR is 5 hours per year. And for each transformer, its FRA is 0.015 and MTTR is 200 per year. Table.2 followed shows the index of load point calculated by this process while Table.3 shows the ones of standards. Then Table.4 the load point index comparison.

Table.2 Load Point Index of Calculation

Load point	λ (time/year)	r (hour/time)	U (hour/year)
LP18	1.694490	5.064860	8.58220
LP24	1.740380	5.029530	8.753320
LP26	1.732380	6.609330	11.449900
LP30	2.256980	6.200710	13.994900
LP33	2.459080	5.187430	12.756300
LP37	2.575080	5.953940	15.331900

Table.3 Load Point Index of Standards

Load point	λ (time/year)	r (hour/time)	U (hour/year)
LP18	1.672500	5.023318	8.401500
LP24	1.721250	5.022658	8.645250
LP26	1.711500	6.709027	11.482500
LP30	2.225000	6.314607	14.050000
LP33	2.537000	5.015372	12.724000
LP37	2.559750	6.142690	15.723750

Table.4 System Reliable Index Comparison

RBT-BUS6	SAIFI (time/year)	SAIDI (h/year)	CAIDI (h/year)	ASAI
Results of calculation	1.98686	11.14200	5.60783	0.998725
Standard results	1.97781	11.46011	5.79433	0.998692

Comparing the calculation results with the ones given by standards [6], the error of load point index is between 0.064% and 4.218% while the error of system reliable index is between 0.003% and 3.219%, maximum error of which is less than 5%. Thus the simulation is definitely accurate.

B. Consequence and Analysis of Distribution System with DGs

Based on feeder line 4 in IEEE RBTS Bus6, two DGs, with the capacity of 3 MW, are installed separately in region 1 and region 2. Table.5 shows typical load point index. Then Table.6 shows system reliable index comparison between system with DGs or not.

Table.5 Typical load point index

Loadpoint	λ	λ	r	r	U	U
	(time/year)	(time/year)	(h/time)	(h/time)	(h/year)	(h/year)
Without DG		With DG	Without DG	With DG	Without DG	With DG

LP18	1.694490	1.532140	5.064860	4.930620	8.582320	7.5554430
LP24	1.740380	1.592110	5.029530	5.000760	8.753320	7.961780
LP26	1.732380	1.579690	6.609330	6.736990	11.449900	10.642300
LP30	2.256980	2.047000	6.200710	5.878600	13.994900	12.033500
LP33	2.459080	1.721770	5.187430	2.824450	12.756300	4.863060
LP37	2.575080	2.191790	5.953930	4.632210	15.331900	10.152800

Table.6 System Reliable Index Comparison

	SAFI (time/year)	SAIDI (h/year)	CAIDI (h/year)	ASAI	ENS (MWh)
Without DG	1.98686	11.14200	5.60783	0.998725	95.34200
With DG	1.70484	8.62515	5.05921	0.998013	68.31667

❖ **Analysis for Table.5 and Table.6:**

- Compared to system without DGs, reliability index of load points in the island are influenced more than those outside the island.
- The introduction of DGs improves the distribution system reliability evaluation index, which demonstrates the benefits brought by the introduction of DGs and islanding schemes.

However, DGs have a large impact on the reliability of load points in the island, causing a dramatic decline of system reliability index. There are several reasons accounting for it. To begin with, failure devices on the main feeder without switches in the island cause interruption to the whole region. But for this paper, failure devices only cause interruptions to customer downstream. What is more, this paper assumes that DGs can supply power during the failure time. In

fact, DGs cannot meet the demand of customers during the failure.

VII. CONCLUSION

This paper presents a sequential Monte Carlo method for calculating the reliability of the distribution system with DGs. Referring to IEEE Std 1547, numerical tests are conducted on RBTS Bus6, illustrating the validity of the proposed method. On the basis of minimal path method, defined in IEEE Std 1366, reliability indices of the system at each load point are calculated, which shows that DGs can improve the reliability of the distribution system dramatically.

References

- [1] ZhaohongBie, Gengfeng Li, Xifan Wang, "Review on Reliability Evaluation of the New Distribution System with Micro-grid", *Electric Power Automation Equipment*, Vol.31, No1, Jan. 2011
- [2] IEEE Power and Energy Society, "IEEE guide for electric power distribution reliability indices," *IEEE Standard 1366 (2012)*.
- [3] Standards Coordinating Committee 21, "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems", *IEEE Standard 1547™*
- [4] Xiaochen Zhang, ZhaohongBie, Gengfeng Li, "Reliability Assessment of Distribution Networks with Distributed Generations Using Monte Carlo Method", *ICSGCE 2011: 27–30*, Chengdu, China, September 2011.
- [5] Shuyun Zhu, "Studies on Reliability Evaluation of Large Wind Farm Integration into Power System," *M.S. thesis*, Xi'an Jiaotong University, China, May 2008.
- [6] Billinton R, Wang P. Teaching distribution system reliability evaluation using Monte Carlo [simulation]. *Power Systems, IEEE Transactions on*, 1999, 14(2): 397-403.