Reliability Evaluation of Active Distribution Systems Including Microgrids

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***Abstract*—This paper proposes a new method for reliability evaluation of active distribution systems with multiple microgrids based on a Monte Carlo simulation. Multi-state models are developed on the basis of generalized capacity outage tables (GCOTs) to better represent various types of distributed generators in reliability evaluation. Then, the virtual power plant (VPP) is introduced to model microgrids with intermittent sources. Furthermore, the reliability behavior of VPP is efficiently characterized by an equivalent GCOT. The nonsequential Monte Carlo method is then adopted to evaluate the reliability of active distribution systems considering different operation modes under single or multiple contingencies. Some techniques—such as two-step state sampling, zone partitioning and minimal path search—are proposed to facilitate the state evaluation process and improve the Monte Carlo simulation speed. The effectiveness and efficiency of the proposed method are validated through extensive numerical tests on an IEEE test system and a real-life active distribution network.**

***Index Terms*—Active distribution network, microgrid, Monte Carlo simulation, reliability evaluation, virtual power plant.**

I. Introduction

MICROGRID, which consists of local distributed generation (DG), load, energy storage, protection and control devices, is an emerging paradigm for effective integration of renewable energy resources into distribution networks [1]. Microgrid can be either interconnected to a distribution grid or operate autonomously as an island when detached from the main power supply by faults or disturbances. As a result, today's distribution systems are evolving from passive networks to active and smarter grids with flexible operation modes [2], [3], which has brought major challenges to the reliability evaluation of active distribution systems. Specifically, the first challenge is how to efficiently and effectively incorporate models for intermittent and uncertain DGs into the reliability assessment. The second is the development of a new evaluation algorithm that is able to deal with highly uncertain, bidirectional power flows caused by embedded microgrids. Moreover, multiple contingencies have to be taken into consideration for active distribution systems, because local microgrids may still sustain even when disconnected from the main grid.

In previous works, the microgrid was often treated as a small-sized conventional power grid where the failure modes of renewable sources were not considered [4]–[7]. These methods are practical for estimating microgrids with combined heat and power plants (CHPs) or conventional generators but are not suitable to analyze distribution networks with wind generators, PVs or other renewable energy sources. The effect of converter topology is incorporated in the reliability evaluation of DC microgrid by the use of minimum cut sets [9]. This approach, however, is inapplicable to the distribution system reliability assessment. Reference [10] has pointed out that modeling the operation mode transitions is a major challenge in the reliability evaluation of microgrids. The reliability of PV/wind integrated microgrid operating in islanded mode was studied using the Monte Carlo simulation [11]. Fault tree analysis (FTA) has been used to evaluate the reliability of islanded microgrids in emergency mode [12]. The limitation is that the FTA can only compute small-scale systems and cannot deal with interconnected situations. It is clear that a multi-state model is needed for modeling PV generators due to the intermittent nature of solar radiation [13]. An analytical approach was proposed [14] to study the effect of DGs on distribution reliability, where the DG output, DG failures and load variations were considered. An event-based Monte Carlo method was developed [15] to evaluate the effect of intentional islanding and switching operations on distribution reliability. The former approach is unable to deal with flexible operation modes of microgrids, and the latter assumes constant loads and DG outputs under islanding situations without considering the intermittent feature of DGs.

This paper proposes a new method for the reliability evaluation of active distribution systems with multiple power sources based on a Monte Carlo simulation. A major contribution is that the concept of the virtual power plant (VPP) is introduced to model microgrids connected with intermittent sources. A nonsequential Monte Carlo method is then adopted to evaluate the reliability of active distribution systems considering different operation modes under single or multiple contingencies. Furthermore, two-step state sampling, minimal path and zone partitioning techniques are proposed to speed up the state sampling process.

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TABLE I
DISTRIBUTION FITTING RESULTS FOR WIND SPEED

Fitted Distribution	Times of being the best fit	% best fit
Weibull	1273	87.19%
Rician	111	7.60%
Rayleigh	74	5.07%
Normal	2	0.14%
Total	1460	100%

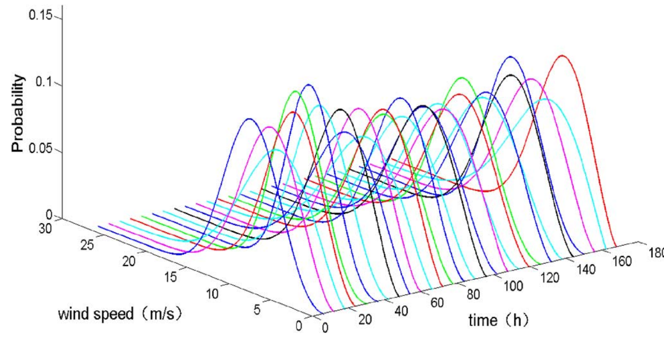

Fig. 1. Six-hourly wind speed probability distributions of one week.

The organization of this paper is as follows: Reliability modeling of renewable sources is introduced in Section II. Reliability evaluation of active distribution network is proposed in Section III. Case studies are presented in Section IV, followed by conclusions in Section V.

II. RELIABILITY MODELS FOR DISTRIBUTED GENERATORS

The models for distributed generators are essential for the reliability evaluation of distribution networks involving microgrids. Accurate models for distributed generators are introduced in this paper to consider the following factors: 1) the randomness and intermittency of renewable energy input, 2) power output characteristics of renewable energy conversion systems, and 3) the impact of the failure and repair characteristics of distributed system components. The reliability model for wind turbine generators (WTGs) is given below as an example. The reliability model for solar photovoltaic farms can be found in [16].

A. High Precision Probabilistic Model for Wind Turbine Generator Power Output

A high precision probabilistic model for wind speed is employed for reliability evaluation. The proposed model provides high-resolution wind speed distributions every 6 h (or even on an hourly basis) rather than a rough Weibull estimation for a whole year. In this paper, the 60-year historical wind speed data measured by NCAR [17] is used to build the wind speed models. The data from NCAR was recorded at the heights of 10 m and 42 m every 6 h. According to the wind shear function, the wind speed sequence at the height of wind turbine hub is obtained [14]

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^n \tag{1}$$

where V_0 is the measured wind speed at the height of H_0, and V is the expected wind speed at the height of H. Here n is the wind shear coefficient, which varies between 0.1 and 0.4 depending on wind speed, roughness of the landscape and aerosphere conditions.

First, wind speed time series per 6-h in the past 60 years are fit by using two-parameter Weibull distribution, Rician distribution, Rayleigh distribution and Normal distribution. Then, the maximum likelihood estimation method is utilized to choose the best fitting function for wind speed probability distribution. The results are shown in Table I.

It is clear that, most of the time, the two-parameter Weibull distribution is the best fit (87.19%), whereas on some occasions, Rician (7.60%), Rayleigh (5.07%), and Normal (0.14%) distributions give better fits. Nonetheless, the likelihood function value of Weibull distribution is always very close to that of the best fit on each of the aforementioned occasions. Thus, it is reasonable to assume that all the wind speeds obey the two-parameter Weibull distribution [15], as follows:

$$F_w(v) = P(V \leq v) = 1 - \exp\left[-\left(\frac{v}{a}\right)^b\right] \tag{2}$$

where a is the scale factor representing average speed; b is the shape factor representing the slope of the distribution; V is the given wind speed value in m/s.

A total of 1460 two-parameter Weibull distribution curves with different parameters are then obtained by fitting 8760 h (total number of hours per year) for 60 years. Fig. 1 shows the 6-hourly wind speed probability distributions for one week. Given adequate historical wind speed data—for example, higher resolution wind speed distributions—hourly Weibull distributions could also be obtained.

Based on the 1460 two-parameter Weibull-distribution curves, the wind speed value of each hour of a year can be sampled through inverse transform method [18]. Note that in the reliability evaluation process, the parameters of Weibull distribution will be updated every 6 h. The wind farm power output can then be obtained from the hourly sampled wind speeds applying wind turbine output curve [19].

B. Multi-State Reliability Model for DG Based on Generalized Capacity Outage Table

A traditional two-state reliability model is unable to capture the inherent randomness and intermittency of renewable energy resources [13]. A multi-state model is developed on the basis of generalized capacity outage table (GCOT) to better represent various types of distributed generators in a reliability evaluation.

To build a multi-state model, the first step is to discretize the power output of DG into several levels using the apportionment method [20] with fixed or variable steps. Second, the probability and cumulative probability at each discrete level are calculated. A 2-MW wind power generator is used as an example to illustrate the modeling process, as shown in Fig. 2. Here the power output data were recorded every 10 min as presented by red points in Fig. 2.

Then, a generalized capacity outage table is generated. Assume that the rated power output of the DG is R_1, the number

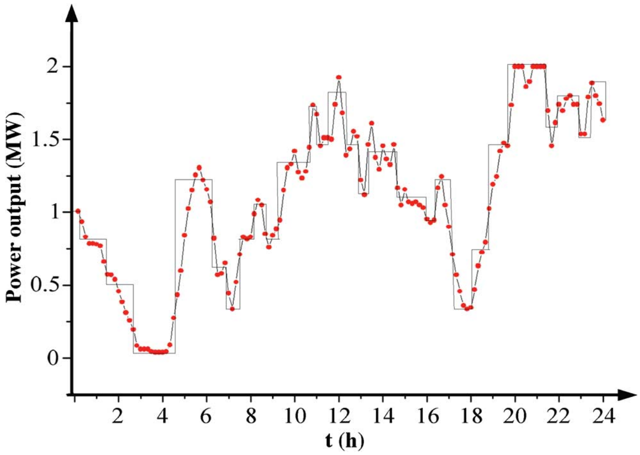

Fig. 2. Discretization of generator power output.

of discrete states is M, and the operating capacity is $C_T(i)$. The GCOT of this wind power generator is expressed as

$$T = \{i, C_T(i), P_T(i), P_T^*(i); i = 0, \cdots, M-1\} \tag{3}$$

where the operating capacity of each state is calculated by

$$C_T(i) = \frac{R_1}{M-1}(M-1-i) \tag{4}$$

the probability of each state is estimated by

$$P_T(i) = \frac{T_i}{T} \tag{5}$$

and the cumulative probability for each state is obtained:

$$P_T^*(i) = \sum_{k \geq i} P_T(k). \tag{6}$$

Here T_i refers to the duration of each state, and T denotes the total time.

After determining the GCOT for each individual DG, an equivalent GCOT representing several DGs considering the forced outage rate (FOR) of DG, feeder and load in a microgrid could be calculated during the microgrid reliability evaluation process. The proposed multi-state reliability model for DGs is suitable for any other types of renewable energy resources such as PVs, tidal generators, etc.

III. Reliability Evaluation of Active Distribution Systems With Multiple Microgrids

Active distribution network and microgrids operate as an integrated system. A microgrid is interconnected to a distribution grid during normal conditions, while during faults or power quality disturbances, it is able to autonomously operate as an island. When operating in islanded mode, a microgrid can supply sufficient power for its priority loads through coordination and regulation of micro power sources according to voltage and frequency requirements. It can be switched back to the interconnected mode once the main distribution grid restores. Therefore, both operation modes need to be appropriately taken into consideration in the reliability evaluation of active distribution networks embedded with microgrids.

A holistic reliability evaluation of both main grid and microgrids should be performed for all scenarios in interconnected mode. On the other hand, when an island exists, the main grid and islanded microgrids have to be evaluated separately, although the reliability indices of the whole active distribution network must be a combination of both parts. Reliability indices of each microgrid could also be listed individually, because these might be useful parameters to facilitate microgrid design and operations.

With embedded microgrids, bidirectional power flows have to be taken into consideration for a reliability evaluation of an active distribution network. Moreover, multiple contingencies should also be considered, because local microgrids may still be able to sustain even disconnected from the main grid. Traditional evaluation methods developed particularly for passive radial networks, therefore, have severe limitations in dealing with modern active distribution networks including microgrids. To tackle these challenges, a new Monte Carlo method is proposed, as detailed below.

A. Microgrid Reliability Model Based on Virtual Power Plant and Generalized Capacity Outage Table

The concept of VPP is employed as a vehicle to facilitate the reliability evaluation of microgrids. An active distribution network may consist of many microgrids, each of which includes autonomous distributed or renewable generators and loads. With detailed representation of every component, the computational burden of the reliability evaluation will become prohibitive. Thus, it is necessary to aggregate all microgrid components into a single entity viz. VPP to offer a simplified equivalent model to be used at distribution grid level.

When integrated into a distribution network, the functionality of a microgrid is to exchange power with the distribution network. The microgrid becomes a power source if it provides more power than the local load and becomes a customer when the load exceeds the available output. Therefore, similar to a conventional power plant, a VPP will be represented by a multi-state model in reliability analysis.

To build the multi-state VPP model, the first step is to establish a GCOT for a microgrid. Then, the post-contingency state of the microgrid, either islanded or connected, can be directly determined from the GCOT. GCOT can also accurately indicate whether an interconnected microgrid is a source or a customer. Fig. 3 illustrates the representation of microgrids 1 and 2 by use of two VPPs connected to the point of interconnection (POI) buses 2 and 5, respectively. Fig. 3(b) illustrates in a certain contingency that VPP 1 acts as a source and VPP 2 a load, as determined by sampling their GCOTs.

It should be noted that failures of energy storage, control, and protection devices in a microgrid can be incorporated in GCOT by considering their impacts on the VPP power output [16].

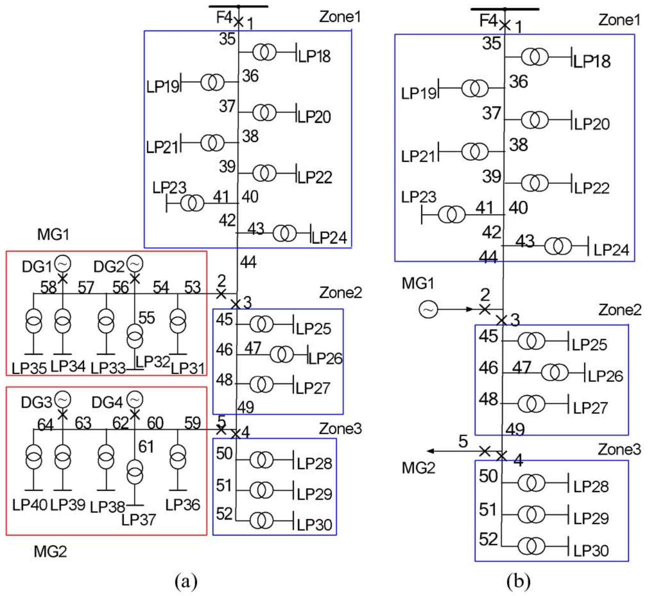

Fig. 3. RBTS Bus6 Feeder4 system. (a) Detailed microgrid diagram. (b) VPP representation of microgrids.

B. Two-Step State Sampling in a Monte Carlo Simulation

An active distribution network may be integrated with multiple microgrids. Several islands may be formed simultaneously after multiple contingencies occur in the network. This is a unique characteristic of a modern distribution network equipped with advanced distribution automation and protection schemes. It is therefore desirable to adopt a Monte Carlo simulation in order to precisely present multiple contingencies and bidirectional power flow caused by multiple power sources.

A two-step state sampling technique is proposed. The first step determines whether all the DGs are up or down based on their FORs. If a DG is down, then its second-step state sampling is skipped.

For instance, denote the FOR of component i as f_i. First, the operating state X_i of component i, can be determined by comparing f_i to a random number generated from the uniform distribution $U(0,1)$, as follows:

$$X_i = \begin{cases} 0 & 0 \le R \le f_i \\ 1 & R > f_i. \end{cases} \quad (7)$$

Here 0 means failure, and 1 means in service.

In the second step of state sampling, the operating capacities of DGs are determined based on their GCOTs. Here the GCOT of a 2-MW WTG shown in Table XI is taken as an example. The second step of state sampling is as follows: A random number is again generated from the uniform distribution $U(0,1)$ and is compared with the cumulative probability of each operating state. For instance, if the random number generated is 0.6431, according to the probability distribution, the operating capacity of this WTG is 0.75 MW.

Traditional one-step state sampling requires complicated recursive convolution of various types of DGs with different FORs, while being unable to accurately model the randomness of multiple microgrids. The proposed two-step sampling method addresses this problem effectively and efficiently.

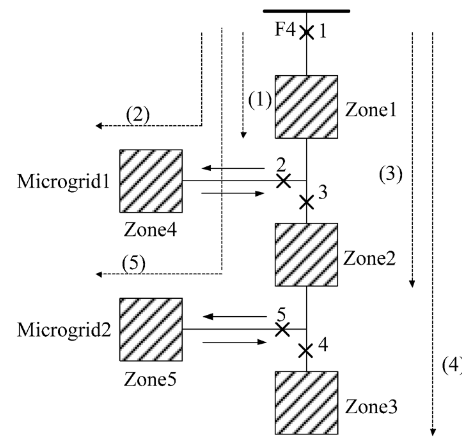

Fig. 4. Schematic diagram of zone partitioning.

C. Zone Partitioning and Minimal Path Search

Zone partitioning and minimal path search are two techniques to facilitate the state evaluation process.

The distribution network is first partitioned into several zones according to the location of switches such as circuit breakers and sectionalizers, as illustrated in Fig. 4.

Secondly, the minimal path of each zone is deduced. A minimal path is a path between a load and a source that, if any branch of this path is taken away, the connectivity is lost. Specifically, for each microgrid or VPP, if faults occur in a zone that is on the VPP's minimal path, then the microgrid will operate in islanded mode. Otherwise, the microgrid will remain connected to the grid.

Note that a load in a microgrid may be supplied by either the main distribution system or the local distributed generators inside the microgrid. Therefore, a two-hierarchy procedure is proposed for minimal path search.

1) Hierarchy I: Searching Minimal Paths on a Microgrid Level:

1.1. Pick one microgrid, and search minimal paths for each load point inside the specified microgrid. Here the minimal path is defined as the path between a local load and distributed source inside this microgrid.

1.2. Repeat step 1.1, and search minimal paths for all microgrids.

2) Hierarchy II: Searching Minimal Paths on a Main Distribution Network Level:

2.1. Pick one load point, and track minimal paths from all source nodes to the specified load point. If any VPP is operating as sources, then this load point will have at least two minimal paths. A VPP operating as a customer will be treated as a load point.

2.2. Repeat step 2.1 for each load point to determine minimal paths for all loads.

D. State Evaluation of Active Distribution Networks

Following the zone partitioning and minimal path search, the state evaluation of the distribution system is performed in two hierarchies.

1) *Hierarchy I: Microgrid Reliability Evaluation:*

- *1.1.* Sample the states of microgrid components including circuits, buses and fuses. Use a two-step state sampling technique to determine the states of all distributed sources (PV array, wind farm, CHP, etc.) that are connected to loads. The output for those disconnected distributed sources is zero.
- *1.2.* For any sampled state, determine the connectivity of minimal paths for each load point inside the microgrid.
- *1.3.* Power output values of all DGs are determined based on minimal paths between all sources and load points and active power balance. Also, the amount of load shedding is determined. The microgrid is considered a VPP working as a power source in the active distribution network reliability evaluation, as below, if the power output of DGs exceeds the load. Otherwise, it is considered a VPP working as a customer.

2) *Hierarchy II: Active Distribution Network Reliability Evaluation:*

2.1. If all VPPs are operating in customer mode, the reliability evaluation degenerates to that of a traditional distribution network. For any non-VPP load point, if any fault occurs on its minimal path, the load will lose power supply. Otherwise, the load will still be supplied by the main source. For any load point inside a VPP, part of the load exceeding the distributed generation capacity will be interrupted if a fault occurs on the minimal path. The load with lower priority will be curtailed first. The total amount of load shed can be determined by the pre-determined load priorities. Any fault outside of the minimal path will not affect the microgrid load.

2.2. If a VPP is operating in source mode, all of its internal loads will still be sustainably supplied even for faults on minimal paths. An island will be formed after the main power supply is lost. In the formed island, some priority loads can still be supplied while others will lose power supply. For load points in a main distribution network, there will be multiple minimal paths.

Reliability for each load point can be calculated by performing the two-hierarchy evaluation above. The reliability indices for the whole active distribution grid, as well as the microgrids, are obtained by summing the load point indices.

The overall procedure of the nonsequential Monte Carlo simulation is illustrated in Fig. 5.

Reliability indices such as ASUI, ASAI, EENS, SAIDI, and SAIFI [21], [22] are calculated in this paper.

IV. Case Studies

Extensive case studies are conducted on the RBTS-Bus6 F4 test system and a real-life distribution system in Northwest China. The influence brought by microgrids has been analyzed in detail. Wind speed correlation and the correlation between solar radiation and load level have also been considered in the evaluation of the real-life system.

A. Modified RBTS Bus6 F4 Feeder

In this case, two microgrids are integrated into the RBTS-Bus6 F4 feeder, as shown in Fig. 3. Microgrid 1 (MG1) includes two wind turbine generators DG1 and DG2, both rated at 2 MW. Microgrid 2 (MG2) includes two thermal power generators DG3 and DG4, also rated at 2 MW. The GCOTs of the four DGs are listed in the Appendix. Detailed test system information can be found in [7].

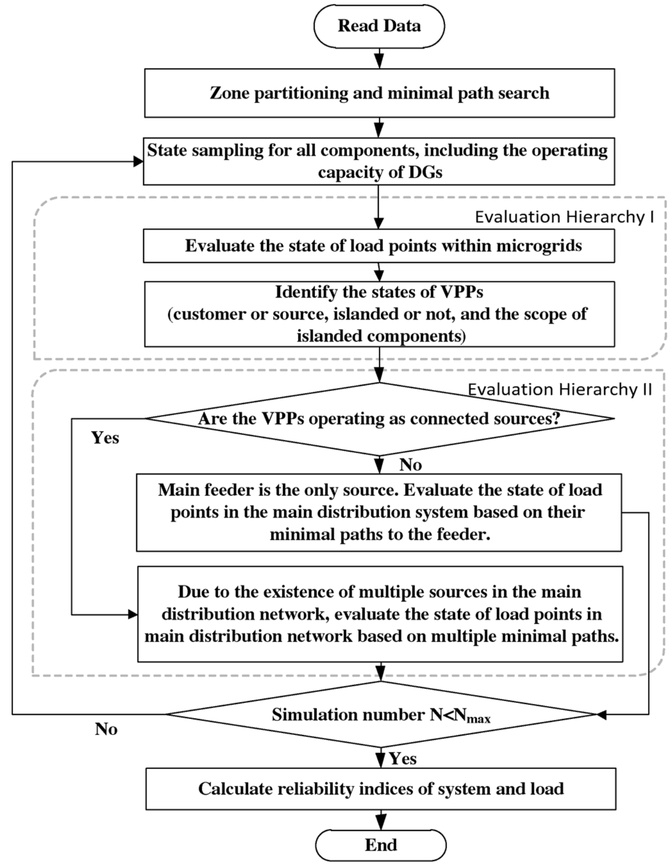

Fig. 5. Overall procedure of simulation.

TABLE II
RELIABILITY INDICES OF MODIFIED RBTS BUS6 F4 FEEDER

Indices	ASUI	EENS(MWh)	SAIDI (h/customer•a)
Microgrid not integrated	0.001326	92.8488	11.6131
Microgrid integrated	0.000827	56.0845	7.24496
% Improvement	37.61%	39.59%	37.61%

Major reliability indices of the modified RBTS Bus6 F4 feeder are summarized in Table II, showing a 40% EENS reduction due to integration of microgrids.

To further analyze the impact of microgrid integration on different regions and load-points, the test feeder is divided into three zones: $MG1$, $MG2$, and *Zone without MG* (including Zones 1, 2, and 3). Reliability results for the three zones are presented in Table III.

Fig. 6 shows that the highest increase of system availability occurs in MG1 and MG2, meaning microgrids do significantly enhance power supply reliability for their local loads.

Reliability indices for every load point in the three zones are summarized in Figs. 7 and 8.

The following can be concluded from Table III and Figs. 6–8:

TABLE III
RELIABILITY INDICES OF THREE ZONES

Zone	Scenario	ASUI	EENS (MWh)	SAIDI (h/customer•a)
Zone without MG	MG not integrated	0.00113368	36.6361	9.93103
	MG integrated	0.000837255	30.9197	7.33435
	% Improvement	26.15%	15.60%	26.15%
MG1	MG not integrated	0.00155506	24.1635	13.6224
	MG integrated	0.000599367	10.407	5.25046
	% Improvement	61.46%	56.93%	61.46%
MG2	MG not integrated	0.00215	32.0491	18.834
	MG integrated	0.000998734	14.7577	8.74891
	% Improvement	53.55%	53.95%	53.55%

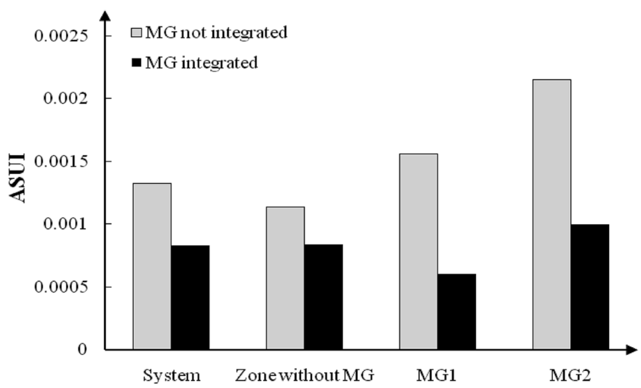

Fig. 6. Change of ASUI after MG integration.

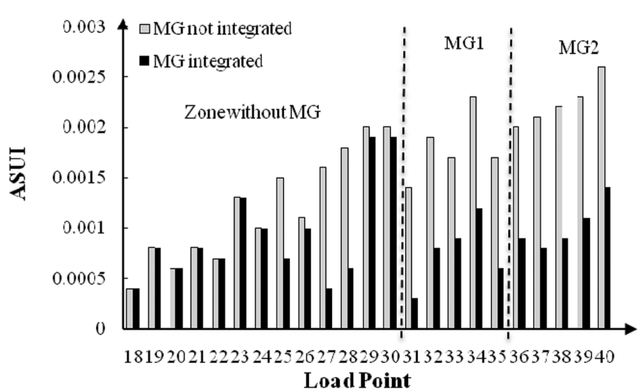

Fig. 7. ASUI of every load point.

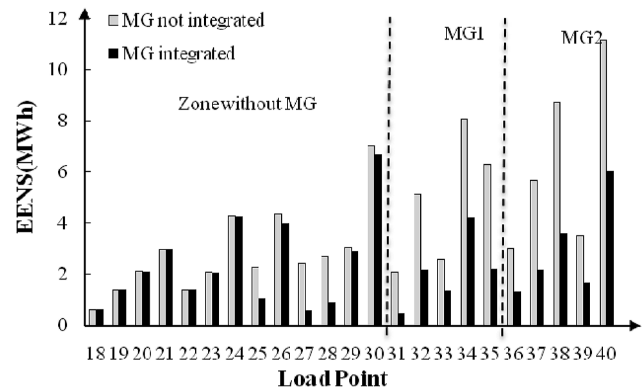

Fig. 8. EENS of every load point.

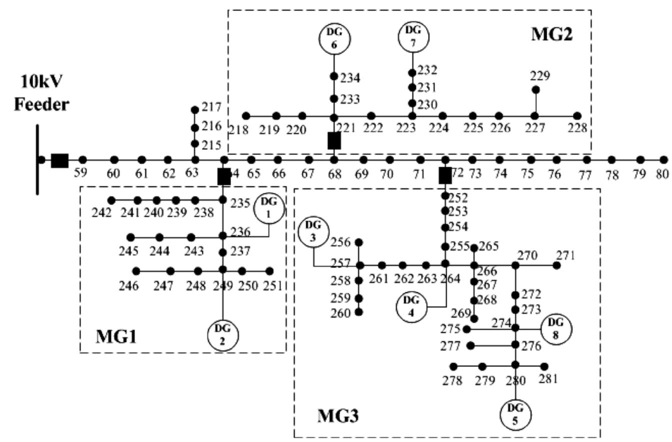

Fig. 9. Real-life distribution system in Northwest China.

TABLE IV
CHARACTERISTICS OF DISTRIBUTED GENERATORS IN THE TEST SYSTEM

Name	Rated Capacity (MW)	Generator Type
DG1	6 (1.5×2+1×3)	wind turbine
DG2	4 (2×2)	gas turbine
DG3	4 (1.5×2+1)	wind turbine
DG4	4 (2×2)	gas turbine
DG5	4 (2×2)	PV array
DG6	5.5 (1.5×3+1)	wind turbine
DG7	4 (2×2)	gas turbine
DG8	2.5 (1.5+1)	wind turbine

1) Both system-level and load-point reliability indices are improved after microgrid integration. In particular, the ASUI of the Zone without MG, MG1, and MG2 are improved by 26.15%, 61.46%, and 53.55%, respectively.
2) The increase rates of reliability indices of MG1 and MG2 are larger than those of the Zone without MG. Therefore, microgrid integration has the greatest impact on its local region.

The level of reliability enhancement for load points outside microgrids varies with locations of microgrids. Load points located in between the two microgrids (load points 25, 26, 27) achieve higher reliability improvement than other non-microgrid load points.

B. Real-Life Distribution System in Northwest China

The proposed method is applied on a 10-kV urban distribution feeder with 89 load points and a total load of 27.683 MW (see Fig. 9). This system is integrated with three microgrids—MG1, MG2, and MG3—with an average load of 6821 kW, 5956.5 kW, and 8236.5 kW, respectively. The three microgrids consist of eight sets of distributed generators, as shown in Table IV. The GCOTs of all three types of DGs are attached in Tables XII–XV in the Appendix.

The GCOT of three microgrids is first obtained. Then, reliability indices are evaluated, and the impact of microgrids on system performance is thoroughly analyzed.

TABLE V
CONFIGURATION OF MICROGRIDS IN THE REAL-LIFE SYSTEM

Name	Total Load (MW)	Total Rated Capacity (MW)	Margin
MG1	6.821	10	31.79%
MG2	5.9565	9.5	37.30%
MG3	8.2365	14.5	43.20%

TABLE VI
GCOT OF MG1 IN THE REAL-LIFE SYSTEM

MG state	Output (MW)	Individual Probability	Cumulative Probability
Source	5	0.0076000	1.00000000
	4	0.1207330	0.99239927
	3	0.3720000	0.87166627
	2	0.2597330	0.49966627
	1	0.0631333	0.23993327
	0	0.0865333	0.17679997
Customer	-1	0.0728000	0.09026667
	-2	0.0128000	0.01746667
	-3	0.0040000	0.00466667
	-4	0.0005333	0.00066667
	-5	0.0000667	0.00013333
	-6	0.0000667	0.00006667

TABLE VII
RELIABILITY INDICES OF THE REAL-LIFE SYSTEM

Scenario	ASUI	EENS (MWh)	SAIDI (h/customer.a)
MG not integrated	0.000657678	152.617	5.76126
MG integrated	0.0003603	92.9789	3.15622
% Improvement	45.22%	39.08%	45.22%

TABLE VIII
ASUI IMPROVEMENT IN DIFFERENT ZONES

Zone	ASUI		Improvement
	MG not integrated	MG integrated	
Zone without MG	0.000424	0.00034933	17.61%
MG1	0.000435294	0.00020392	53.15%
MG2	0.000572549	0.00025490	55.48%
MG3	0.001026667	0.00051778	49.57%

1) GCOT for Microgrids: The overall characteristics of the microgrid are shown in Table V. Each microgrid has a high capacity margin (rated generation over load) of more than 30%. However, due to the intermittency and randomness of renewable energy sources, these margins are not always available.

For instance, the GCOT of MG1 in Table VI shows a 9% chance that this microgrid will operate as a customer absorbing power from the grid. The GCOTs for MG2 and MG3 are omitted due to limited space.

2) Indices Evaluation: The reliability indices are assessed for the base system without any microgrids and for the real reinforced system with integration of microgrids. Results are summarized in Table VII.

Again, the real-life network is divided into four zones: *Zone without MG*, $MG1$, $MG2$, and $MG3$. The improvement of ASUI is shown in Table VIII.

3) Considering Wind Speed Correlation: It is necessary to consider wind speed correlation because wind turbine generators on the same feeder may locate in close proximity. The approach described in [23] is used to incorporate wind speed correlation in the reliability evaluation of active distribution systems.

Reliability indices with different wind speed correlation coefficients p are shown below.

4) Considering Correlation Between Solar Radiation and Load Level: The output of PV array changes with time because of the variation of solar radiation. In the meantime, the load level may also vary. Therefore, the correlation between solar radiation and load level should be considered in the reliability evaluation.

It should be noted that the time-dependent characteristic of solar radiation has already been considered in building the outage table of the 2-MW PV (see Table XV). As illustrated, the cumulative probability of an operating capacity below 0.01986 MW is as high as 0.625913.

After analyzing the load profile, a two-level load model is used to incorporate the time-dependent effect. The daytime load level is 124% of the average load, while the nighttime level is 76%. It is assumed that if the sampled output of PV array is below 0.01986 MW, the nighttime load level is adopted in simulation.

Wind speed correlation coefficient p is set at 0.4. The comparative analysis results are documented in Table X.

The following conclusions are reached:

1) According to Tables VII and VIII, the reliability indices of the whole system are considerably improved by the integration of microgrids, because the load points will still be supplied by DGs even when the main feeder is unavailable.
2) As can be observed in Table VI, the probability of MG1 functioning as a power source is 90.97%. Therefore, the integration of microgrids not only provides power supply for load points within the microgrid, but also for load points in the main distribution system. As a result, reliability indices in the Zone without MG are also improved.
3) Further analysis of the probabilities in Table VI reveals that the power output values of microgrids are most possibly between 0 and 3 MW. In fact, the probabilities for MG1, MG2, and MG3 operating in this range are 69.49%, 83.58%, and 49.65%, respectively. This means that the supply capability of microgrids to external load points is limited. This leads to a modest reliability improvement for loads outside microgrids.
4) Table IX shows that the reliability benefits brought by microgrids decrease as the degree of wind speed correlation increases. Wind speed correlation has a considerable impact on reliability indices, meaning that the assumption of full independence between wind turbines results in overoptimistic reliability indices. Thus, the correlation effect should be considered in the evaluation process in order to get realistic and accurate results.
5) Table X reveals that system reliability slightly improves after considering the correlation between solar radiation and load level. The positive correlation between PV output and load level contributes to this improvement. The reliability evaluation method proposed in this paper, therefore,

TABLE IX
RELIABILITY INDICES WITH DIFFERENT WIND SPEED CORRELATION LEVELS

p	ASUI	EENS(MWh)	SAIDI(h/customer.a)
1	0.000422	106.853	3.69448
0.8	0.000409	105.212	3.58357
0.6	0.000385	98.4428	3.37563
0.4	0.00039	99.8933	3.41722
0.2	0.000381	98.1527	3.34097

TABLE X
RELIABILITY INDICES CONSIDERING CORRELATION BETWEEN SOLAR RADIATION AND LOAD LEVELS

Scenario	ASUI	EENS(MWh)	SAIDI(h/customer.a)
Two Load Levels	0.000388	98.2201	3.39642
Average Load	0.000390	99.8933	3.41722
% Improvement	-0.51%	-1.67%	-0.61%

TABLE XI
OUTAGE TABLE FOR A 2-MW WIND TURBINE GENERATOR

State No.	Operating Capacity (MW)	Individual Probability	Cumulative Probability
1	2	0.0094	1
2	1.75	0.0321	0.9906
3	1.5	0.0474	0.9585
4	1.25	0.0764	0.9111
5	1	0.1114	0.8347
6	0.75	0.1518	0.7233
7	0.5	0.1703	0.5715
8	0.25	0.1659	0.4012
9	0	0.2353	0.2353

TABLE XII
OUTAGE TABLE FOR A 1.5-MW WIND TURBINE GENERATOR

State No.	Operating Capacity (MW)	Individual Probability	Cumulative Probability
0	1.5	0.008447	1
1	1.25	0.060388	0.991553
2	1	0.093836	0.931165
3	0.75	0.157078	0.837329
4	0.5	0.216324	0.680251
5	0.25	0.224886	0.463927
6	0	0.239041	0.239041

TABLE XIII
OUTAGE TABLE FOR A 2-MW THERMAL GENERATOR

State No.	Operating Capacity (MW)	Individual Probability	Cumulative Probability
0	2	0.972254	1
1	0	0.027746	0.027746

can be used to quantify the reliability benefits and load carrying capability of PV generation systems. Note that, in order to incorporate the PV-load correlation more accurately, sequential modeling and simulation may have to be used.

TABLE XIV
OUTAGE TABLE FOR A 1-MW WIND TURBINE GENERATOR

State No.	Operating Capacity (MW)	Individual Probability	Cumulative Probability
0	1	0.008562	1
1	0.75	0.149087	0.991439
2	0.5	0.274201	0.842352
3	0.25	0.343151	0.568151
4	0	0.225	0.225

TABLE XV
OUTAGE TABLE FOR A 2-MW PV ARRAY

State No.	Operating Capacity (MW)	Individual Probability	Cumulative Probability
0	2	0	1
1	1.765214	0.028311	1
2	1.508182	0.026484	0.971689
3	1.221198	0.026826	0.945205
4	0.979598	0.021119	0.918379
5	0.794954	0.024543	0.89726
6	0.630221	0.025	0.872717
7	0.486252	0.02774	0.847717
8	0.36345	0.036187	0.819977
9	0.257938	0.039726	0.78379
10	0.164521	0.047489	0.744064
11	0.082311	0.070662	0.696575
12	0.001986	0.625913	0.625913

V. CONCLUSIONS

A new method for reliability evaluation of active distribution systems with multiple microgrids is presented based on a Monte Carlo simulation:

1) This paper contributes a multi-state reliability model for microgrids based on a GCOT and the proposed multi-state reliability model for DGs, which properly and precisely addresses the randomness in distributed sources. The model is suitable for any other types of renewable energy resources such as PVs, tidal generators, etc.
2) Furthermore, a major contribution is that the concept of the VPP is introduced to model microgrids connected with intermittent sources. The VPP offers a simplified equivalent model to be used at distribution grid level. It also can be easily combined with the multi-state reliability model obtained by the GCOT.
3) A two-hierarchy Monte Carlo simulation method is proposed to evaluate the reliability of active distribution networks on both the microgrid and main grid levels. Two-step sampling, zone partitioning and minimal path search techniques are employed to accelerate the state sampling and evaluation process in the Monte Carlo simulation.
4) The proposed model and method have been applied to the RBTS test feeder and a real-life distribution system in Northwest China. Numerical results have validated the effectiveness of this method.

APPENDIX

The GCOTs for the five types of DGs in Section IV-B are given in Tables XI–XV, respectively.

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