

# Research on the Improved Reliability Evaluation Method of Active Distribution System

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**Abstract.** The reliability of active distribution system is important for power system operation and users convenient. In order to evaluate the reliability of distribution system quickly and effectively, this paper established the output model of photovoltaic generation system and wind turbine generators considering more random factors. Then considering that the calculating complexity bring by above model and Monte Carlo method, this paper provided network simplification method based on feeder partition. Then this paper designed parallel calculation project for reliability evaluation to improve calculating efficiency. At last, simulation example verified the effectiveness of active distribution system reliability evaluation.

## 1. Introduction

Active distribution system is one of the distribution systems which can increase renewable energy and distributed energy. The features of distribution system will affect the reliability of the distribution system[1], such as AC and DC distribution form, the kinds of distributed generators(DG), the sustainable generating ability and demand response. The reliability evaluation method of traditional power system cannot adapt to the new features, so it is important for researching on reliability evaluation of active distribution system.

Reference [2]established the reliability model of DG combined with stored energy, and realized evaluating the reliability of microgrid distributed system based on sequential Monte Carlo simulation. The model of DG and loads in this paper were too simple for application. Reference[3-5]built the reliability model of microgrids generating system based on the factors such as correlation of DG output, forced outage and nonlinear output. Monte Carlo simulation verified the effectiveness and generality of the model, but the complex model increased the computational complexity. Reference[6] built the coordinative optimization model of load- stored energy device considering electricity price and used the model combined with Monte Carlo simulation method. The reliability evaluation results of this paper approached the practical microgrids operation, but the calculating complexity would increase correspondingly. Reference[7]established a short-term interrupt model of main feeder and distributor considering the affection of protection system to microgrids reliability, and used non-sequential operating state to simulate reliability evaluation. Above all, simulation method such as Monte Carlo could simulate the characteristics of loads and devices flexibly, so it has strong adaptability for evaluating active distribution system. But along with the increasing of distribution system nodes and kinds, numbers, the simulation method for reliability evaluation will treat huge data calculation and the time calculation needing will increase rapidly. Parallel calculation is an effective method to solve the time wasting problem. Parallel calculation has been used in some fields such as



power flow calculation, safety analysis, risk assessment[8]. The parallel calculation has more adaptability for simulation reliability evaluation.

This paper established the output model of photovoltaic generation system and wind turbine generators considering more random factors. Considering that the calculating complexity bring by above model and Monte Carlo method, this paper provided network simplification method based on feeder partition. Then this paper designed parallel calculation project for reliability evaluation to improve calculating efficiency. At last, simulation example verified the effectiveness of active distribution system reliability evaluation.

## 2. The improved model of DG

### 2.1 The output model of photovoltaic power generation system

The output of photovoltaic power generation system depended on many factors. For convenience, the steady power of PV modules could be affected by external conditions such as irradiation, environmental temperature and rated capacity[9]. The output power could be expressed as formula (1).

$$P_{PV} = P_{STC} \frac{S}{S_{STC}} [1 + K(T - T_{rate})] \quad (1)$$

In formula (1),  $S$  means irradiation.  $P_{STC}$  means the rated power of normal condition.  $S_{STC}$  means the irradiation of normal condition.  $k$  means the temperature coefficient.  $T$  means the working temperature of solar panels.  $T_{rate}$  means the normal temperature.

According to reference [9], considering the decreasing power operation caused by failure of photovoltaic array, the output model of  $m \times n$  PV matrix could be expressed as formula (2).

$$P_{VT}(t) = P_{STC}(t) \frac{S_{std}(t) + \Delta S(t)}{S_{STC}} [1 + k(T_{std}(t) + \Delta T(t) - T_{rate})] \quad (2)$$

In formula (2),  $\Delta S(t)$  means the difference between irradiation and the standard radioactivity curve.  $\Delta T(t)$  means the difference between temperature and the standard temperature curve.

### 2.2 The random output model of wind turbine generators

The wind speed modelling is the key factor for getting the output of wind power. Considering the minimum wind speed limit in the same time period, this paper used third order Willbur distribution as the wind speed model.

$$f_t(v) = \begin{cases} \frac{b}{a} (v - c(t))^{b-1} e^{-\left(\frac{v-c(t)}{a}\right)^b} & v > c(t) \\ 0 & v \leq c(t) \end{cases} \quad (3)$$

In formula (3),  $v$  means the wind speed.  $a$  means the scale parameter which affects the average wind speed.  $b$  means the shape parameter which affects the distribution curve.  $c(t)$  means the position parameter,  $c(t) < \min v(t)$ .

The wind speed parameters could be obtained by least squares method, method of moments estimator and maximum likelihood estimation method[9]. The  $v(t)$  could be obtained by inverse transformation.

Combined with wind speed model, the output power model could be obtained on the basis of wind turbines operating model, which is expressed as formula (4).

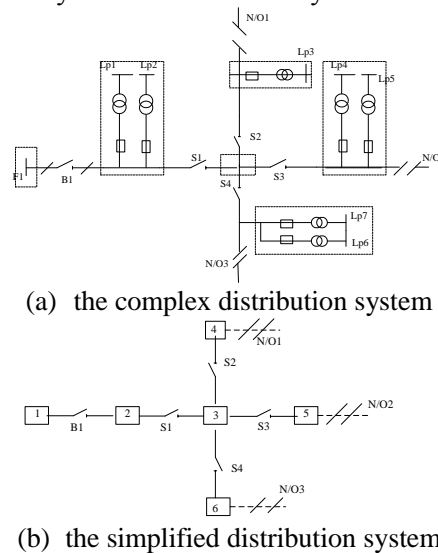
$$P_W = \begin{cases} 0 & v \leq v_{ci} \cup v \geq v_{c0} \\ P_R \frac{v - v_{ci}}{v_R - v_{ci}} & v_{ci} < v \leq v_R \\ P_R & v_R < v < v_{c0} \end{cases} \quad (4)$$

In formula (4),  $v_{ci}$ ,  $v_{co}$ ,  $v_R$  mean the cut in wind speed, the cut out wind speed and rated wind speed.  $P_R$  means the rated power of wind turbine generators.

### 3. The feeder partition method

The traditional reliability method of distribution network should enumerate all the devices including distribution transformers, overhead lines and cables. The equipment number of distribution network is large, analysis for every equipment will cost large calculation, so it is important to simplify the system.

The network simplification of this paper uses switchgear equipment as boundary to divide distribution network and at the same time, all the sub-distribution systems could be regarded as zone nodes. A complex distribution was shown as figure 1(a), which had 2 branch feeders and 3 connected switches. As figure 1 showed, F1 was the bus bar of substation. B1 was circuit breaker and S1~S4 were sectional switches. Lp1~Lp7 were loads nodes. N/O1~N/O3 were loop switches. The devices in the dotted line frames were sub-distribution systems. Figure 1(b) was the simplification of figure 1(a). All the sub-distribution systems could be regarded as zone nodes. By simplification, the number of devices was reduced, so the reliability evaluation efficiency could be improved greatly.



**Figure 1.** The complex distribution system and its' simplification system

## 4. The reliability evaluation of distribution network based on parallel calculation

### 4.1 Sequential Monte Carlo simulation

Sequential Monte Carlo method could construct the state duration sequence and realize multistate simulation of active distribution network by system decision.

#### 1) The construction of state sequence Monte Carlo simulation

Network devices (such as lines, transformers, converters and disconnectors) reliability evaluation model usually used two-state models, which ignored transient failures. The device operating time and repairing time in failure state obeyed exponential distribution. The construction of state sequence included two steps.

Step 1: Hypothesis that all the devices are in the operating state. The non-failure time and failure repairing time could be obtained by sample according to failure rate and repairing time. Considering the active distribution system island operating state caused by public distribution system failure, Assuming that the failure rate  $\lambda_s$  and repairing rate  $\mu_s$  were constants, then

$$\lambda_{eq} = \lambda_s + \lambda_D \quad (5)$$

$$\mu_{eq} = \frac{\lambda_{eq} \mu_s \mu_D}{\lambda_s \lambda_D + \lambda_D \mu_s + \lambda_s \mu_D} \quad (6)$$

In formula (5) and (6),  $\lambda_D$  and  $\mu_D$  mean the failure rate and repairing rate of grid connected switches.

Step 2: According to the non-failure operating time and repairing time of devices, construct the system state duration sequence  $S_{sd}=[S_k, d_k]^T$ ,  $K \in [1, N_{sys}]$ ,  $N_{sys}$  is the system state numbers.  $S_k$  is the state combination of  $k$ th devices.  $d_k$  is the duration time.

## 2) System state judgment

For a system operating state  $(s_k, d_k)$ , the judgment process was shown as below.

Step 1: Loads nodes. The loads nodes of active distribution system could be divided into connecting-grid loads, interrupted loads nodes and island loads nodes. The reliability of connecting-grid loads was ensured by public distribution system. Interrupted loads had non-connected pathway with DG and connecting-grid loads, so the power supply would be interrupted. The power supply of island loads was supported by DG and stored energy.

Step 2: Island operating topology identification. In order to improve the applicability of every topology structure in public distribution system and island operating running condition, this paper designed a limited priority aggregation (LPA) method to realize operating topology judgment. LPA method could choose the island nodes by aggregating the network nodes according connected domain.

Step 3: Simulating loads. Sampling simulation could get the output of loads according to the reliability models of DG and loads.

Step 4: State updating of the system. Update the system state of current hour including island controlling and SOC devices.

## 4.2 The design of parallel calculation scheme

In order to improve calculating effectiveness, traditional Monte Carlo method designed the parallel calculation strategy using fixed cycle times. Every circulation is independent. The calculating result was collected by main server. The traditional parallel calculation would encounter redundancy. In order to improve the calculation effectiveness to a large extent, this paper provided the dynamic parallel calculation method. When the sampling sample  $X^*$  was sure, the calculation of the random variables was independent and had little influences. So the method can improve calculation effectiveness further more.

Different from the traditional parallel calculation with fixed cycle times, this paper made the variance convergence as the judgment basis. The main server formed the final sample matrix using sampling method and allocated the sample value of  $X^*$  to all the sub-servers for calculation.

In the process of calculation, assumption that the numbers of servers is  $p$  and the ID of every server is 0 to  $(p-1)$ . The ID of main server is 0 and other ID numbers are servers for parallel calculation. I means initializing working. T means one Monte Carlo task. C means convergence controlling. S means stopping the simulation. F means calculating and outputting the reliability indexes.

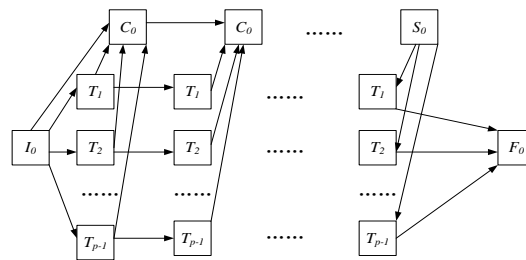
As the figure 2 showed, after the initializing working I0, the main server will send the random quantity of sample  $X^*$ . Receiving the calculating task, the sub-servers complete their calculating tasks and send results to the main server. The main calculating steps are shown as below.

(1) Initializing working.

(2) The main server formed the final sample matrix  $X^*$  using sampling method and send calculating tasks to sub-servers.

(3) Sub-servers selected a system state from sample matrix  $X^*$  and marked the random quantity avoiding repeating calculation. Then topology analysis and power flow calculation would be completed according to the state system. After the state analysis, a next random quantity would be gotten for the next calculation until all the random quantity calculated.

(4) All the sub-servers send their calculating results to main server. The main server read the calculating results and judged if the calculation reached the convergence precision. If the calculation satisfied the convergence condition then send stopping command  $S_0$  to sub-servers and all the sub-servers would stop calculation and send the residual result to main server. At the same time the main server carried out command  $F_0$  and generated the reliability indexes. Otherwise, the calculation would jump to step (2) and continue the calculation until the ending conditions are satisfied.



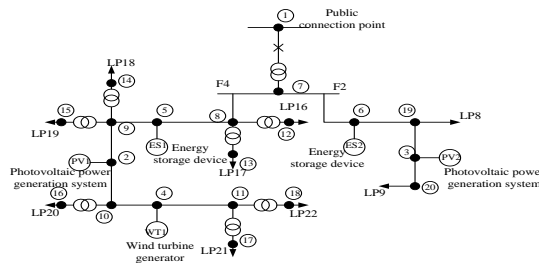
**Figure 2.** The schematic diagram of parallel calculation

## 5. Simulation example analysis

### 5.1 The test system and its' parameters

This paper selected two feeders of RDTS Bus2 system[10] and allocated it into an active distribution system, which is the test system of this paper and the structure was shown as figure 3. The test system had a wind turbine generator with 1MW capacity, 2 photovoltaic power generation systems with 0.8MW capacity and 2 stored energy devices with 0.36MW capacity. The maximum charging and discharging power was 0.12MW. The average loads power of all the nodes was 4.936MW. The operating environment parameters were obtained by a certain area of Shandong. The loss cost coefficient of all the energy stored devices was same.

The device failure rate, repairing rate and the user number of loads nodes could be obtained by reference [10]. The failure rate and repairing time of power were shown as table 1. The reliability evaluation indexes of active distribution system were system average interruption duration index (SAIDI), expected energy not supplied (EENS) and system average interruption frequency index (SAIFI).



**Figure 3.** Test system for reliability evaluation

**Table 1.** Reliability data of power sources

Power sources/devices	Failure rate (time $\cdot$ a <sup>-1</sup> )	Average repairing time/h
Public distribution system	2.00	4.5
Photovoltaic array	0.05	5.0
Photovoltaic converter	0.12	70.0
Wind turbine generator	0.25	60.0
Energy storage device	0.12	20.0

### 5.2 The calculation results and analysis

The simulation time was selected as 350a, the serial calculation and parallel calculation were both done after network simplification. The reliability evaluation results were shown as table 2.

**Table 2.** The comparison of different evaluation methods

model	EENS/	SAIDI/	SAIFI/	Calculatingtime/
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	$((\text{MW}\cdot\text{h})\cdot\text{a}^{-1})$	$(\text{h}\cdot\text{a}^{-1})$	$(\text{time}\cdot(\text{subscriber}\cdot\text{a})^{-1})$	s
Serial method with non-simplification	50.8903	11.2976	1.7827	2039.799
Serial calculation after network simplification	49.2986	11.5285	1.7267	1796.271
Parallel calculation	50.2831	12.9532	1.7936	238.219

According to the comparison of table 2, the network simplification method based on feeder partition could improve calculating efficiency and keep the accuracy invariant. Using the parallel calculation method, the calculating efficiency could be improved greatly. At the same time calculating accuracy could be kept stable. In this paper, when the number of workers was 16, the parallel calculation efficiency could be improved 86.75% compared with serial calculation. The example analysis verified the practicality of the method proposed by this paper.

## 6. Conclusion

This paper established the output model of DG and provided the network simplification method of feeder partition. Then this paper provided the active distribution reliability evaluation method based on parallel Monte Carlo simulation. At last, the simulation example verified the effectiveness and practicality the method of this paper, which could be used in complex distribution system reliability evaluation.

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