International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0968

RISILIENCE EVALUATION OF DISTRIBUTION NETWORK CONSIDERING FAULT REPAIR

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ABSTRACT

Resilience is used to assess the ability to maintain and recover system performance in an extreme weather, which is one of the most important performance indicators of smart grid. A model for evaluating the hurricane resilience of distribution network considering fault repair is proposed. First, the difference between toughness and reliability is described. Second, to perfect the resilience assessment and analysis method of distribution systems, a component failure probability model under hurricane condition is built, the latin hypercube sampling is used to reduce the failure scenes and a distribution network restoration model considering fault repair is established. Finally, a simulation verifies the validity and accuracy of the proposed approach in this article.

Keywords: resilience, distribution network, distributed generation, fault repair

NONMENCLATURE

Symbols	
D	Set of restored load
N	Number of scenes
T	Time of failure
ω_i	Weighting factor
L(t)	Actual system function at time t
TL(t)	Original system function at time t
$P_{Di}(t)$	The restored load at bus i at t time
V	Wind speed
R	The distance between a line and the hurricane center
R_{max}	The radius along the region of the maximum wind
V_{Rmax}	The maximum speed
N_1	Wind load
B	The diameters of the external conductor wires
θ	The angle between the wind vector and the line
p_{fl}	Failure probability of the wire
p_{lp}	Failure probability of the pole
$P_{l,i}(V)$	Failure probability of line i
T_j	Actual repair time of fault j
β	Number of faults repaired at the same time
Ω	Maximum number of faults available for simultaneous repairs
T_{RE}	Expected to repair time of fault j
P_{Gi}	Generator injection active power at bus i
Q_{Gi}	Generator injection reactive power at bus i
x_{ij}	Binary variable representing the health state of line ij
P_{ij}	Active power of line ij
Q_{ij}	Reactive power of line ij
V_i	Voltage at bus i
g_{ij}	Conductance of line ij
b_{ij}	Susceptance of line ij
V_{min} V_{max}	Maximum and minimum voltage
$P_{Gi,min}$ $P_{Gi,max}$	Maximum and minimum of DG output
$P_{Di,max}$	Maximum active load of bus i
g_{Tj}	Current distribution network operation structure
G	Set of distribution network radial structure
C	Set of distribution network connectivity structure

1. INTRODUCTION

Self-recovery ability is the self-recovery ability of the grid after suffering from severe natural disasters. As one of the important landmark performances of the smart grid, it has been highly concerned by the power academic community and industry. For example, an attack from a hurricane disaster will cause a large number of line trips, barrows and broken bars to cause major economic and social losses. Therefore, how to effectively evaluate and improve the resilience of power grids, reduce the impact of disasters, and improve the ability to recover after disasters is one of the key issues for the development of smart grids.

Some scholars have carried out certain research on the evaluation of the resilience of distribution networks in extreme weather[1-8]. Gao H *et al* [1] proposed a resilience assessment matrix that evaluated the resilience of distribution networks from four dimensions: technology, organization, society, and economy; defined resilience indicators based on area, probability, and regulation costs, and developed distribution network resilience planning and scheduling measures based on this. Karin A *et al* [2] used the non-homogeneous Poisson process to simulate the amount of extreme weather that the distribution network may suffer during the year and evaluate the reliability of the distribution network. Ouyan M *et al* [3] constructed an annual elasticity index based on the actual annual load curve of the distribution network and the target annual load curve to evaluate the resilience of the distribution network, and established a probability model for finding multiple faults in the distribution network, but there is no significant difference between the elasticity index its proposed and the traditional distribution network reliability index, and only single failure analysis is selected for analysis, which is not representative. Huang G *et al* [4] used Monte Carlo to find the fault scene and set the component failure rate threshold to screen the fault scene, but did not establish the hurricane and distribution network component failure rate model.

Based on the above research, a resilience evaluation method for distribution network considering fault repair is proposed in this paper. This paper first describes the concept of resilience and the difference from reliability. Then we establish a relationship model between hurricane wind speed and component failure rate to quantify the impact of extreme weather on distribution network components. Third, the resilience evaluation process of distribution network is proposed, which uses the Latin hypercube sampling and synchronous back-reduction method to screen the fault scene and considers the fault repair in the fault recovery stage. Finally, a set of simulations verifies the validity and accuracy of the proposed approach in this article.

2. THE DIFFERENCE BETWEEN TOUGHNESS AND RELIABILITY

Resilience considers the ability to minimize load loss under extreme weather conditions; reliability describes the ability to meet user power requirements under normal operating conditions. The two describe the fault state characteristics of the distribution network from different angles. High reliability distribution network does not necessarily have high resilience. Specifically, the difference between resilience and reliability is shown in Tab. 1.

Tab1 The Differences Between Resilience and Reliability

Comparison Terms	The Differences Between Resilience and Reliability	
	Resilience	*Reliability*
Time scale	Durations of extreme weather events	Measured in year
Blackout frequency	Related to the fragility of components	Related to failure times /year of components
Blackout level	Multiple faults which have high probability to occur	Single faults oriented
The way of restoration	Faults repaired and DG supplying	Load transfer and faults repaired
The impacts of DG	Critical load can be supplied by DG under extreme weather, so DG has more significance to resilience.	

This paper describes a resilience metric (AR) as the ratio of the area between the real performance curve and a time axis to the area between the target performance curve and the time axis. This ratio considers the time of restoration in normal conditions and extreme weather conditions (i.e., having outage-caused load losses during the disaster).

$$AR == \sum_{n=1}^{N} \frac{\int_0^T L(t)dt}{\int_0^T TL(t)dt} / N \tag{1}$$

$$L(t) = \sum_{i \in D} \omega_i P_{Di}(t) \tag{2}$$

Equation 2 indicates that the system function at time *t* is the weighted sum of the loads which are restored at that time.

3. DISTRIBUTION NETWORK RESILIENCE EVALUATION

3.1 Resilience evaluation process

1) Input distribution network structure and related parameters, use Monte Carlo simulation to extract hurricane scene and calculate component failure probability;

2) Generate fault scene set by using Latin hypercube sampling;

3) Solve the optimal fault repair plan and islanding scheme in each scenario;

4) Calculate the weighted sum of the recovered load in each scenario;

5) Calculate system resilience metric after completing analysis of all scenarios.

3.2 Component failure probability model

Wind speed and direction (influenced by the hurricane) can be obtained based on the Batts wind field model:

$$V=\begin{cases} V_{R_{\max}} r/R_{\max} & r\le R_{\max} \\ V_{R_{\max}}(R_{\max}/r)^{0.7} & r>R_{\max} \end{cases} \tag{3}$$

The wind load N_1 can be determined by a speed and direction:

$$N_1 = 1.2\times\frac{V^2}{1.6}B\sin^2\theta \tag{4}$$

An overhead wire is easy to become interrupted, the stress on the wire section is proportional to the sum of the wire wind load and the gravity load. The load on the pole is the largest at the root of the rod. The bending moment of the rod is the vector of the root moment caused by the wind load of the shaft and the wind load of the conductor. The calculation method is as shown in [9], the failure probability can be expressed as:

$$\begin{cases} p_{fl}=\int_0^{\sigma_g}\frac{1}{\sqrt{2\pi}\delta_l}\exp\left[-\frac{1}{2}(\frac{\sigma_l-\mu_l}{\delta_l})^2\right]d\sigma_l \\ p_{fp}=\int_0^{\mathrm{M_T}}\frac{1}{\sqrt{2\pi}\delta_p}\exp\left[-\frac{1}{2}(\frac{M_p-\mu_p}{\delta_p})^2\right]dM_p \end{cases} \tag{5}$$

The normal operation condition of the distribution line is that the wire and the pole are working normally, so the distribution line is equivalent to the series model. The likelihood that an overhead distribution line is damaged by extreme weather events can be expressed as follows:

$$p_{l,i}(V)=1-\prod_{k=1}^{m_1}(1-p_{fp,k,i}(V))\prod_{k=1}^{m_2}(1-p_{fl,k,i}(V)) \tag{6}$$

3.3 Latin hypercube sampling

Latin hypercube sampling is a stratified random sampling method that could generate a finite number of samples from a multi-dimensional distribution. First, divide the cumulative distribution of each variable by Y equally spaced intervals; then randomly select a value from each interval, and randomly pair these values to generate an equal probability scene, so as to ensure that the sampling points are evenly distributed in the distribution of variables. When Y is large, small probability events can also be randomly drawn, avoiding the phenomenon that small probability events are missed in random sampling. In addition, latin hypercube sampling has improved the problem of large number of repeated sampling due to random sampling and improved the efficiency of sampling. The specific working principle can be found in [10].

3.4 Distribution network restoration model considering fault repair

After the end of the extreme disaster, the fault repair and power restoration alternately coordinate to restore the power supply of the power loss load. This paper establishes a power restoration model for the DG distribution network considering fault repair. Among them, the upper layer model optimizes the fault repair sequence; the lower layer model optimizes the fault recovery scheme.

3.4.1 Upper layer model

The upper layer model aims to minimize the total load loss during the entire process:

$$\min f_1=\sum_j(T_j\sum_{i\in D_j}\omega_i P_{Di}) \tag{7}$$

Constraints that need to be met include repair resource constraint and repair time constraint:

$$\beta\le\Omega \tag{8}$$

$$T_j\le T_{RE} \tag{9}$$

After the fault repair plan is developed by the upper layer model, it is passed to the lower layer model. When there is a faulty component repaired, the network status would be changed, the lower layer model should re-establish the island partition, DG output and load reduction scheme.

3.4.1 Lower layer model

The lower model aims at minimizing the load loss at a certain stage:

$$\min f=\sum_{i\in D_j}\omega_i P_{Di} \tag{10}$$

Constraints that need to be met include power balance constraint, bus voltage constraint, branch current constraint, DG output constraint, load reduction constraint, island connectivity constraint and radial constraint:

$$\begin{cases} P_{Gi}-P_{Di}-\sum_{j\in\Psi_{bi}}x_{ij}P_{ij}=0 \\ Q_{Gi}-Q_{Di}-\sum_{j\in\Psi_{bi}}x_{ij}Q_{ij}=0 \end{cases} \tag{11}$$

$$\begin{cases} P_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \\ Q_{ij} = -V_i^2 b_{ij} - V_i V_j (g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij}) \end{cases} \tag{12}$$

$$V_{\min} \le V_i \le V_{\max} \tag{13}$$

$$P_{ij,\min} \le x_{ij} P_{ij} \le P_{ij,\max} \tag{14}$$

$$P_{Gi,\min} \le P_{Gi} \le P_{Gi,\max} \tag{15}$$

$$0 \le P_{Di} \le P_{Di,\max} \tag{16}$$

$$g_{T_j} \in G \tag{17}$$

$$g_{T_j} \in C \tag{18}$$

4. CASE STUDY

4.1 Test Network and Weather Regions

This section presents the results of the proposed method applied to a distribution network close to the coast in the northern hemisphere. The length and direction of lines, the peak and priority of load are shown in Fig 1. The coordinates are established based on the origin of Feeder F3's outlet.

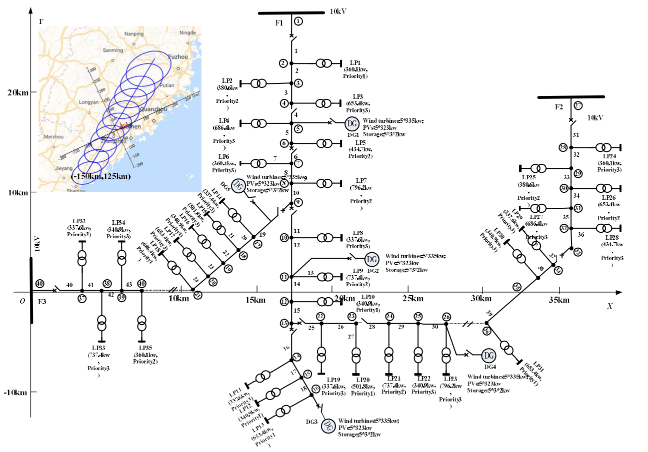
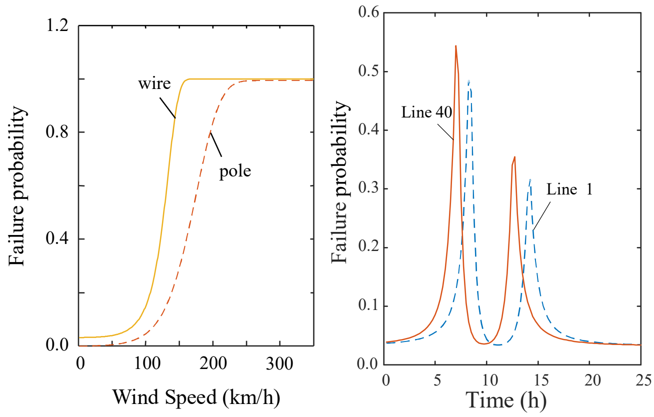


Fig 1 The distribution network

It is assumed that a hurricane lands at the location (-150km, -125km) and moves with a translational speed of 20km/h. The blue line represents the track of the hurricane center and the circles indicate the boundary of the radius of maximum wind for the traveling hurricane at a specific location. The origin shows the location of the test system. The simulation starts at the time when hurricane lands and the fault lines are repaired after hurricane.

4.2 Component failure rate simulation results

According to the component failure probability model, the relationship between the probability of failure and the wind speed is shown in Fig. 2(a). The time-varying failure probability of each line affected by the hurricane (taking lines 1 and 40 as an example) is shown in Fig. 2 (b), the hurricane landing time is the simulation start time



(a) (b)

Fig 2 Failure probability-wind speed curves of lines

It can be seen from Fig. 2(a) that when the wind speed is greater than 120km/s, the failure probability of the wire and the pole will increase significantly. As the hurricane approaches, the wind speed on the line gradually increases. However, when the line is inside the maximum wind speed radius, the wind speed decreases, so the time-varying fault probability curve in Figure 2(b) shows two spikes. During the entire process affected by a hurricane, when the line is near the maximum wind speed radius, it is most prone to failure.

4.3 Distribution network resilience evaluation analysis

We consider one of the scenarios where lines 3, 28, 37 and 42 fail after 7.25h, 8.25h, 8.5h and 13.5h after the hurricane lands, respectively. The load curve and impact area for the scenario is obtained. The recovery processes for the three cases are different as shown in Fig 3. The dotted line is the target load curve under normal conditions.

Case 1 is the real load curve without any enhancing strategies and the repair sequence of fault lines is the same as the fault sequence.

Case 2 enhances the resistance capacity by allowing the distribution network to access DG. The repair sequence is the same as in case 1.

Case 3 optimizes the repair sequence.

After one or more lines are damaged, the load associated with the failure line are also lost during the most severe situation, the real load is only about 15% of target load in normal conditions. In case 3, more 2MW loads (than in case 2) can be supplied after the second component is repaired. Compared to case 1, a 5MW extra load is supplied in case 2 during the most severe of situations, which indicates that a DG can significantly improve distribution network resilience.

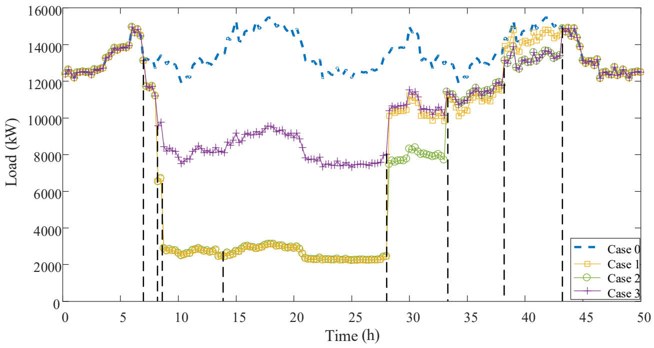


Fig 3 Systems load curves distribution network in extreme weather

Calculate the resilience of the distribution network in the three cases according to the procedure in 3, as shown in Tab. 2.

Tab 2 Resilience of distribution system in different cases

Resilience metric	Distribution System Resilience		
	Case 1	Case 2	Case 3
AR	0.572	0.775	0.789

Only 57.2 percent of the load in normal condition can be supplied during extreme weather. Case 3 recovered 3.4 percent more load than case 2 due to optimization of the fault component repair plan.

5. CONCLUSION

A model for evaluating the hurricane resilience of distribution network considering fault repair is proposed in this article. The case study shows that the wind direction and wind speed of the hurricane have a great influence on the component failure probability. The DG and fault repair plan have also a great influence on resilience of distribution network. The proposed resilience evaluation method in this article is significant and can quantitatively evaluate the disaster-resisting ability of the distribution network, and it is also the basis for the research on the resilience improvement strategy of distribution network.

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