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Published in:
IEEE Access

Link to article, DOI:
10.1109/ACCESS.2018.2872941

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Luo, D., Xia, Y., Zeng, Y., Li, C., Zhou, B., Yu, H., & Wu, Q. (2018). Evaluation Method of Distribution Network Resilience Focusing on Critical Loads. IEEE Access, 6, 61633-61639. DOI: 10.1109/ACCESS.2018.2872941

IEEE Access
Multidisciplinary ⁞ Rapid Review ⁞ Open Access Journal

Received August 19, 2018, accepted September 22, 2018, date of publication October 1, 2018, date of current version November 9, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2872941

Evaluation Method of Distribution Network Resilience Focusing on Critical Loads

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This work was supported by the National Natural Science Foundation of China under Grant 51722701.

ABSTRACT With the frequent occurrence of extreme weather events in the world, the ability of power system to resist disasters has attracted more attention. In this paper, a method to evaluate the resilience of distribution networks by focusing on the impact of critical loads under extreme weather events is proposed, and typhoon is taken as the representative to formulate a vulnerability curve of components. Furthermore, the Monte Carlo method is used to simulate the whole process of extreme weather disaster and to generate the fault scenario. Different weights are assigned to different levels of load according to the importance of load, and the weighted loss of load is selected as the evaluation index of resilience. Finally, the method is verified by the IEEE-33 bus system. The results demonstrate that this method is effective to quantify the resilience of distribution networks under extreme weather events.

INDEX TERMS Extreme weather events, distribution network, critical loads, resilience evaluation, component fragility.

I. INTRODUCTION

In 1973, Holling first proposed the system-level definition of resilience, measuring whether the system could reduce system losses during disturbances and quickly return to normal state when the disturbance is over [1]. In recent years, many natural disasters and man-made attacks have brought unprecedented challenges to the power system, resulting in large-scale continuous blackouts, highlighting the incompetence of power systems in handling serious extreme events. In 2008, more than 129 lines were damaged by ice disasters in southern China, and power facilities in 13 provinces and cities were destroyed, resulting in power outages for 14.66 million households; In 2016, a tornado hit in Jiangsu Province, China, causing 135,000 households to lose power [2]. Therefore, to research the impact of extreme weather events on the power system and to measure the effectiveness of countermeasures under disasters, the concept of resilience was introduced into the power system, and then the power system's ability to deal with extreme weather events was evaluated [3]. As the distribution network has the closest relationship with the user's production and life, the resilience of the distribution network is mainly manifested by the support and recovery ability of the critical load in the distribution network under extreme weather events [4]. Evaluating the resilience of the distribution network and researching the impact of extreme weather events on the distribution network is of great significance to safeguarding people's production and life and resisting disasters. At present, researches on the resilience of distribution network mainly start from the following aspects.

The impact of extreme weather events on the distribution network was researched. The frequency of various extreme weather events was researched and the damage degree of various extreme weather events to the power system was analyzed in [5]. A spatiotemporal distribution model between meteorological conditions and grid faults was constructed in [6]. The effects of various human events on the power system were researched in [7].

Evaluation framework of system resilience was researched. The effects of wind and load conditions on the failure probability of transmission lines were researched and the resilience of power system was evaluated in [8]. Reference [9] used load frequency loss and load expected loss to evaluate the effectiveness of different power systems resilience enhancement measures. In [10], resilience was defined as the probability that a power system performs its intended function in the presence of a component failure.

In addition, to reduce the losses caused by extreme weather events on the distribution network, measures have been put forward to improve the resilience. In [11], a three-stage optimization model was constructed, and a method for determining the optimal reinforcement position and reinforcement strategy was proposed. In [12], an optimized location scheme aiming at battery energy storage and photovoltaic power generation which could optimize the resilience of power system was proposed to improve the accessibility of energy and energy capacity during extreme events. A microgrid optimal layout model was proposed in [13], which determines the optimal size and location of the microgrid in the power system to maximize the resilience of the system.

The evaluation of resilience is the basis of resilience research. The existing methods mainly evaluate it from the following four aspects:

Robustness: The ability of the system to withstand disturbance events while maintaining its own function.

Redundancy: The ability of the system to use system equipment or backup equipment during a disturbance event.

Resourcefulness: The ability of the system to invest resources such as manpower and material resources to maintain critical functions under disturbance events.

Rapidity: The ability of the system to quickly return to the desired normal state and reduce power outage losses after encountering a disturbance event.

At present, the research on the resilience of distribution network is all to evaluate the ability of all loads to withstand disasters under extreme weather events. However, in the distribution network, it is not necessary to ensure the power supply for full load under extreme weather events, as long as there is enough power available to a certain proportion of critical loads. Moreover, the resilience of the distribution network mainly represents the support and recovery ability of the critical load. For this problem, a method to evaluate the resilience of distribution networks by focusing on the impact of critical loads under extreme weather events is proposed. This is a significant advantage of this method when compared with the previous methods, e.g., the resilience trapezoid. It could effectively reflect the support capacity of the distribution network for critical loads and better reflect the resilience of the system by considering different weights for each level of load. In this paper, typhoon is taken as the representative to build a vulnerability curve of components. The Monte Carlo method is used to simulate the whole process of extreme weather disaster and to generate the fault scenario. Different weights are assigned to different levels of load according to the importance of load, and. the weighted loss of load is selected as the evaluation index of resilience. Finally, the method is verified by the IEEE33 bus system.

II. QUANTIFICATION OF THE IMPACT OF EXTREME WEATHER EVENTS

The typhoon weather is taken as an example to research the impact of extreme weather events on the distribution network. Under the typhoon weather, faults of the distribution network are mainly line disconnects and power poles collapse. The main reason is that the wind speed of the typhoon exceeds the standard wind speed of the line design. Therefore, it is necessary to simulate the wind speed under the influence of typhoon. The more developed Batts model is used to simulate in this paper [14]. The wind speed at each point in the typhoon wind field of the Batts model is,

$$V = \begin{cases} V_{R_{\max}}(R_{\max}/R)^{0.6}, & R > R_{\max} \\ V_{R_{\max}}R/R_{\max}, & R \le R_{\max} \end{cases} \tag{1}$$

where V is the typhoon wind speed, $R_{\max}$ is the maximum wind speed radius, $V_{R\max}$ is the wind speed at the maximum wind speed radius point, R is the distance from the point to be researched to the typhoon center point.

The failure rate of distribution network components is related to line component strength and load effects. The strength of the distribution network components determines load effects on the distribution network lines. Generally, the tensile strength of the wire and the flexural strength of the concrete pole are subject to a normal distribution, and the probability density function could be formulated as follow,

$$f_R(x) = \frac{1}{\sqrt{2\pi}\delta}\exp[-\frac{1}{2}(\frac{x-\mu}{\delta})^2 \tag{2}$$

where the values of μ and δ could be obtained through actual operation experience or material pull-off experiments.

Under the typhoon weather, the overhead line in the distribution network line is prone to disconnect at the highest suspension point. The load effect of the wire is the stress σ_g on the section of the wire at the highest suspension point under wind load. The value is the ratio of the highest suspension point tension to the cross-sectional area of the wire, which is proportional to the vector sum of the wind load and the gravity load. In the distribution network line, the pole is easy to fall and break at the root of the rod. The load effect of the pole refers to the bending moment M_T at the root of the pole caused by the load that the distribution network is subjected to. The value is the vector sum of the bending moment caused by the wind load of the wire and the wind load of the shaft.

Under the typhoon weather, the unit length wind load that the distribution network component is subjected to could be formulated as follow [15],

$$P = \frac{V^2}{1.6}D\alpha\mu_{sc}\mu_Z\sin^2\theta \tag{3}$$

where D is the outer diameter of the wire, α is the wind pressure non-uniformity coefficient, μ_{sc} is the wire shape coefficient, μ_Z is the wind pressure height variation coefficient, θ represents the angle between the wind direction and the distribution network line.

According to the strength of the line component and the load effect, the reliable running probability of the component could be computed, and then the failure rate of the pole and the failure rate of the wire could be computed through p_p and p_l, respectively.

$$\begin{cases} p_{\mathrm{p}} = \int\limits_0^{M_T} \frac{1}{\sqrt{2\pi}\delta_{\mathrm{p}}} \exp[-\frac{1}{2}(\frac{M_{\mathrm{p}}-\mu_{\mathrm{p}}}{\delta_{\mathrm{p}}})^2]\mathrm{d}M_{\mathrm{p}} \\ p_{\mathrm{l}} = \int\limits_0^{\sigma_g} \frac{1}{\sqrt{2\pi}\delta_{\mathrm{l}}} \exp[-\frac{1}{2}(\frac{\sigma_{\mathrm{l}}-\mu_{\mathrm{l}}}{\delta_{\mathrm{l}}})^2]\mathrm{d}\sigma_{\mathrm{l}} \end{cases} \tag{4}$$

The line failure rate of the overhead distribution network could be formulated as follow [11],

$$p_k(V) = 1 - \prod_{i=1}^{n}(1 - p_{\mathrm{p}ik}(V))\prod_{j=1}^{m}(1 - p_{\mathrm{l}jk}(V)) \tag{5}$$

where $p_k(V)$ is the failure rate of line k, n is the number of poles of line k, m is the number of wire of line k, $p_{\mathrm{p}\,ik}(V)$ is the failure rate of the ith pole of line k, $p_{\mathrm{l}jk}(V)$ is the failure rate of the jth wire of line k.

III. FAULT SCENARIO GENERATION AND LOAD IMPORTANCE CLASSIFICATION

A. GENERATION OF FAULT SCENARIO UNDER EXTREME WEATHER EVENTS

Under extreme weather events, the probability of failure of the distribution network is greatly increased. In the evaluation of the resilience of the distribution network, it is necessary to research the fault scenario of the distribution network. The Monte Carlo method is used to simulate the whole process of extreme weather, and to generate fault scenario under extreme weather events. Details are as follows:

Assuming that the number of distribution network components is N, the operating state of the distribution network components could be represented by an N-dimensional vector.

$$X = [x_1, x_2, \cdots, x_N] \tag{6}$$

The operating state of each component x_a ($a = 1, 2, \ldots, N$) of the distribution network could be represented by a random number r uniformly distributed in the interval [0, 1].

$$x_a = \begin{cases} 0, & r > p(V) \\ 1, & 0 \le r \le p(V) \end{cases} \tag{7}$$

Sampling with repetition M times, a set of containing M distribution network system status samples is available:

$$S = (X_1, X_2, \cdots, X_M) \tag{8}$$

The above-mentioned set is the scenario in which the distribution network fails at a certain moment under extreme weather events.

B. CLASSIFICATION OF CRITICAL LOAD AND LOAD SHEDDING OPERATION

According to the "Design Specification for Power Supply and Distribution System", the load of each bus is graded and classified into first, second, and third level load through the analysis of the importance of system load. For example, the first level load is the most important load, the second level load is the general important load, and the third level load is the normal load. The resilience of the distribution network mainly represents the support and recovery ability of the critical load. In order to quantify the resilience of the distribution network focusing on the critical load, different weights are assigned to different levels of load buses (the first level load is 6, the second level load is 3 and the third level load is 1) to indicate that the impact of different grades of load on the evaluation of the resilience of the distribution network is different.

When the system line is overloaded, it is necessary to perform load shedding operation on the existing load. In order to ensure the safe operation of the system, the sheared load should be kept as little as possible, and the critical load in the system should not be sheared as much as possible. Detailed steps are as follows:

Step 1: The topology of the distribution network after the fault is layered, and the topology is searched according to the level. When an overload situation is found in a certain line, the power of the overload is computed by comparing with the limit transmission power.

Step 2: The load shedding combination is selected, and the third level load is first removed, ensuring that the removed load is greater than or equal to the overload power and the sheared load is minimized. If the third level load is still unable to meet the requirements, then the second level load is removed. Analogy until the requirements are met.

Step 3: The process continues to search for the line according to the hierarchy until there is no overload line in the topology.

C. QUANTITATIVE RESILIENCE EVALUATION METHODOLOGY

In this paper, the comprehensive load loss after the weight processing of all grades of load buses under extreme weather events is used to reflect the resilience of the distribution network system. It considers the loss of system failure during extreme weather and the affected time of the distribution system.

The landing process is divided into several time periods through predicting the detailed information of typhoon weather. The wind speed and wind direction of the location where the distribution network components are located at each time period are simulated by combining the typhoon model. The load effect of the components and the strength of the components are computed. The influences of the extreme weather events on the distribution network are quantified, and the failure rate of the distribution network line under extreme weather events is obtained.

By classifying the bus according to the load importance of the distribution network system, different weights are assigned to the corresponding load bus to distinguish the importance level, and the comprehensive load loss focusing on the critical bus is researched to evaluate the resilience of the distribution network.

In order to capture the random behavior of the extreme weather events and the influence it brings, Monte Carlo simulation is used to construct the resilience evaluation model. Compared with traditional Monte Carlo simulations, in each simulation step of the method in this paper, a weather-based component failure rate is used instead of using a constant and weather-independent component failure rate. In each simulation step, the component failure rates in the distribution line are provided by their vulnerability curves which represent the component failure rate as a function of the weather parameters. A map of weather parameters is mapped to the component vulnerability curve to obtain a time-varying failure rate of the distribution network component in each simulation step. In each simulation step, the number in the range [0, 1] is randomly generated and is compared with the component failure rate to obtain the distribution network line fault condition of each scenario in the current time period. Since the fault condition of the previous period will affect the operation of the system during the current period, a fault recovery time is set to indicate the continuous impact of the fault. All possible paths from the critical load bus to the power supply bus are searched by depth at first. The power flow is used to obtain the line overload situation in the current scenario. The load shedding is performed according to the load shedding strategy. And the comprehensive load loss focusing on the critical load in the current scenario is computed according to the weight. The above steps are repeated for each time period until the set accuracy is reached to simulate the occurrence of various fault scenarios, so as to obtain the average loss of system load in each period, and then the resilience index R of the distribution network during the extreme weather is computed. The detailed process of the distribution network resilience evaluation method is depicted in Figure 1.

$$R = \frac{1}{LOSS} \tag{9}$$

$$LOSS = \int_{0}^{t} \frac{\frac{1}{M}\sum_{i=1}^{M} \Delta p(X_i)}{P_0} dt \tag{10}$$

$$\Delta p(X_i) = 6 \cdot \Delta p_1(X_i) + 3 \cdot \Delta p_2(X_i) + 1 \cdot \Delta p_3(X_i) \tag{11}$$

where $\Delta p(X_i)$ is the comprehensive load loss focusing on critical load in a certain scenario at a certain moment, $\Delta p_j (j = 1, 2, 3)$ is the load loss of each level in a certain scenario at a certain moment, and M is the sampling number. X_i is the fault scenario under extreme weather events, and P_0 is the initial weighted total load of the distribution network.

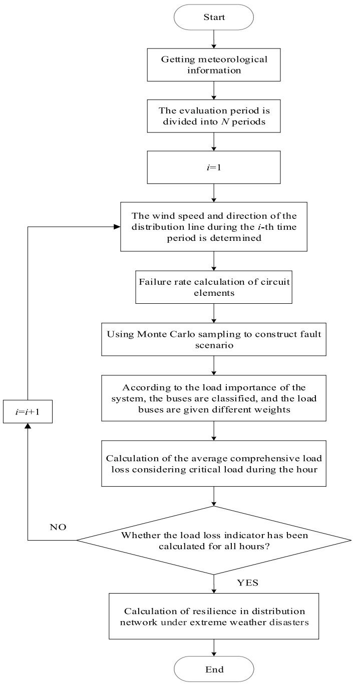

FIGURE 1. Detailed process of evaluation method.

IV. CASE STUDY

The IEEE33 bus system is used to analyze the resilience of distribution network under extreme weather events [15]. Figure 2 shows the modified IEEE33 bus system network frame structure diagram. The coordinate system is established with the bus 1 as the origin. Each line is 5km long and the average span is 50m. The distribution network line adopts LGJ-240/30 wire. The rod is made of 12m concrete pole with a strength class of G. The landing coordinates of typhoon are (−125km, −40km). The typhoon moves along the positive direction of the x-axis at a speed of 25km/h. The typhoon landing time is the simulation start time. Since the overhead line could not be automatically reclosed after a rod failure or line disconnect, the average line repair time is 5 hours [16]. According to the proposed distribution network resilience evaluation process, the evaluation period is one hour.

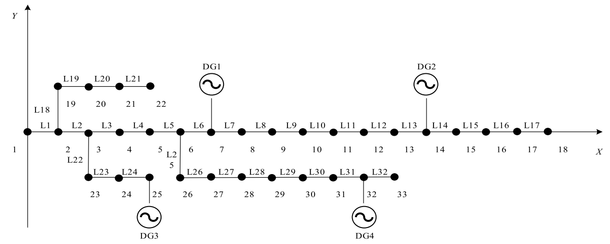

FIGURE 2. Network frame structure diagram of IEEE33 bus system.

Assuming that four distributed generations generally installed at the end of the distribution network and the bus with critical loads are connected to the distribution network system. The detailed installation locations and capacities are depicted in Table 1.

TABLE 1. **Distributed generation access location and installation capacity.**

DG	Access Location	Installation Capacity /kW
1	7	400
2	14	300
3	25	400
4	32	200

The fragility curve of the wire and the pole obtained according to the distribution network component failure rate model mentioned above is depicted in Figure 3.

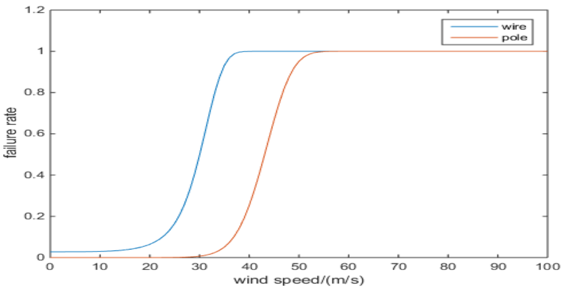

FIGURE 3. **Component vulnerability curve of distribution network.**

It could be obtained from the above figure that as the typhoon wind speed increases, the failure rate of the system components gradually increases. When the vertical wind speed of the line is greater than 30 m/s, the failure rate of the system components rapidly increases. As the typhoon approaches the distribution network line, the wind speed on the line increases continuously. When the distance between the line and the typhoon center is less than the maximum wind speed radius, the wind speed on the line decreases. When the line is near the maximum wind speed radius of the typhoon, the line is most prone to failure.

The load importance of the IEEE33 bus system is divided as depicted in Table 2.

TABLE 2. **The rank of load importance of IEEE33 bus system.**

first level load bus	second level load bus	third level load bus
6、7、13、14、24、25、30、32	2、8、12、16、19、20、21、23、27、31、33	The rest

With the access of distributed generation, power supply to critical loads of the distribution network during disasters is ensured, increasing the resilience of the system in the face of disasters. The resilience value of the system is increased from 0.0893(not connected to the distributed generation) to 0.1738 through the example. The loss rate of the system load with the distributed generation connected to the distribution network is depicted in Figure 4.

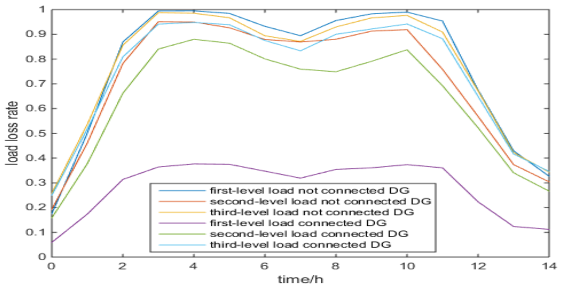

FIGURE 4. **Load loss rate of system buses under the typhoon weather.**

Figure 4 shows the load loss rate of the first level and second level loads is significantly lower than that of the non-connected distributed generation. This is because the distributed generation could form an island and still has the power supply capacity for the nearby critical load under extreme weather events. It ensures the power supply for the system's critical load and improves the system's resilience under extreme weather events. The case study shows that the method proposed in this paper has reasonable results and high credibility.

Mobile emergency generators are critical flexibility resources of distribution systems for resilient emergency response to natural disasters. Assuming that the No. 4 distributed generation is replaced by a mobile emergency generator with the same capacity. When the bus 32 is in normal operation, the mobile emergency generator could move to a nearby important node to provide power supply. Compared to the previous case, the resilience value of the system is increased from 0.1738 to 0.1764 through the example. It could be seen that the access of the mobile emergency generator improves the power supply to the critical load of the distribution network during the disaster, and increases the flexibility of the system in the face of disasters.

Next, the effectiveness of the evaluation method is verified by the common distribution network resilience enhancement measures.

Scheme 2 strengthens the line 1 so that it does not fail, but actually it only reduces the line failure rate [17].

Scheme 3 improves the fault repair speed through the smart grid technology such as fault detection and positioning, IT communication, and shortens the repair time by 20% [18].

It could be seen from Table 3 that the resilience index of the two measures is higher than the resilience value of the original system. It also could be seen from Figure 5 that the

TABLE 3. **Performance of common distribution network resilience enhancement measures.**

Scheme	Enhancement Measure	Resilience
1	The original system	0.1738
2	Reinforcement line 1	0.1990
3	Improve the speed of fault repair	0.1988

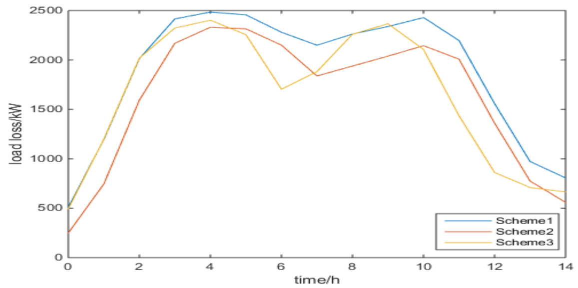

FIGURE 5. **Comparison of system bus load loss under the typhoon weather.**

load loss area of the two measures is smaller than the original system. The reinforcement of line 1 in scheme 2 ensures the normal power supply of bus 2, also ensures the power supply reliability of the critical line 1, and the power supply capacity of the whole system is improved, so the load loss during the typhoon impact process is reduced. Scheme 3 shortens the maintenance time after the line fault, so that the load loss curve of the system moves forward as a whole, which reduces the probability of multiple failures in the system and increases the resilience of the system. The case study demonstrates the effectiveness of the resilience evaluation method proposed in this paper.

V. CONCLUSIONS

In this paper, a method to evaluate the resilience of distribution networks by focusing on the impact of critical loads under extreme weather events is proposed. The load loss rate of the system before and after the access of the distributed generation and the resilience variation of the distribution network are compared and analyzed. The effectiveness of the proposed method is verified by evaluating the common resilience enhancement measures. The method proposed in this paper is of great significance for the reasonable evaluation of the resilience of the distribution network and the reduction of fault losses in the distribution network under extreme weather conditions. This method could be used as a basis for researching other resilience enhancement measures, and could also provide reference for a stronger resilience distribution network. Future work includes the cosimulation of transmission and distribution networks, and how to combine the measures to improve resilience with the costs used to obtain the most economical improvements, which will help get a better understanding of a wider range of aspects that could affect the resilience performance of a power system as a whole.

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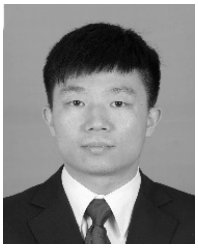

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