Distribution Network Multi-time Scale Resilience Index Framework Considering Generation-Grid-Load-Storage Resources

Zhi Li[1], JiaSheng Peng[2](✉), Youhang Yang[2], and Yunfeng Wen[2]

[1] Zhejiang Huadian Equipment Testing Institute Co., Ltd., Hangzhou 310000, China
[2] College of Electrical and Information Engineering, Hunan University, Changsha 410082, China
jspeng0822@hnu.edu.cn

Abstract. In recent years, natural disasters have become increasingly frequent, which has brought huge losses to the power system. Researchers use resilience to assess the ability of distribution networks to respond to natural disasters. In order to evaluate the resilience of distribution network under extreme natural disasters, this paper proposes a multi-time scale resilience index framework considering the generation grid load storage resources. Firstly, the connotation of resilience is introduced, and the whole process of resilience of distribution network in response to extreme natural disasters is described; Secondly, a resilience index framework that comprehensively considers the time scale and the generation grid load storage resources is proposed. The time level index is divided into three levels according to disaster events: preventive resilience, resistance resilience and recovery resilience. The generation grid load storage resources describe the resilience index from four aspects of the source side, network side, load side and storage side respectively; Then this paper introduces the calculation method of some indicators and the calculation process of resilience indicators. Finally, some resilience indicators are calculated using IEEE 33-node test feeder. These cases verify the effectiveness and feasibility of the index system.

Keywords: Extreme Natural Disasters · Resilience Evaluation Index System · Multi-Time Scale · Generation-grid-load-storage Resources

1 Introduction

In recent years, all kinds of extreme natural disasters with low probability and high loss have occurred frequently [1], which has not only seriously affected the stable operation of the power system, but also caused huge economic losses. As an important part of power system, distribution network undertakes the important task of directly distributing electric energy to end users. Due to the problems of weak grid structure, poor quality of distribution equipment and low level of operation and maintenance in the distribution network, and with the access of wind power, photovoltaic electric vehicles and energy storage, the uncertainty of the distribution network is increasing. When dealing with

P. Zeng et al. (Eds.): CUS-EPSA 2022, LNEE 1030, pp. 175–186, 2023.
https://doi.org/10.1007/978-981-99-1439-5_15

natural disasters with low probability and high loss [2] such as typhoon, ice disaster, earthquake and some network attacks, large-scale power outages will occur. Therefore, for such small probability and high loss events, it is necessary to evaluate the resilience of distribution network to analyze the resilience level of distribution network under extreme events, and build a resilient distribution network to deal with various extreme events.

Resilience has been applied to many disciplines, such as biology [3], environmental science [4], economics [5] and so on. In the research of electric power system, resilience is defined as the ability of power system to prevent, resist and quickly [6] restore load for small probability high loss extreme events. Compared with traditional reliability, reliability mainly focuses on typical faults with high probability and low loss, and mainly focuses on the impact of typical faults on power failure of users, while resilience mainly focuses on extreme events with small probability and high loss, which not only focuses on the impact of power failure on users, but also focuses on the rapid recovery ability of the system.

In order to analyze the resilience level of distribution network, it is necessary to propose relevant indicators to evaluate and calculate the resilience of distribution network. Based on the system function curve and considering the probability of extreme events, there have been many relevant studies on resilience indicators in China. Journal articles [9] considers the electro pneumatic coupling system, and puts forward the coupling vulnerability index, structural vulnerability index and operation vulnerability index; Journal articles [10] takes the typhoon disaster of natural disaster as an example, summarizes the current research status of distribution network resilience index under the condition of single meteorological disaster at home and abroad, believes that the evaluation resilience should mainly be expressed from the ability to maintain normal operation and recover as soon as possible, and puts forward the prospect of establishing a multi period and multi-dimensional resilient index system; Journal articles [11] associated with the resilient modeling of springs in mechanics, proposed the resilient index of distribution network by analogy, proposed the equivalent branch model, and analyzed the force of the model, and finally obtained the resilient coefficient index considering the power supply state of the system. This index can effectively quantify the application ability of the corresponding demand in the recovery process, but the application scenario of this index is relatively limited.

In addition, many foreign scholars have carried out research on resilience indicators, journal articles [7] proposed a probability resilience index, which can comprehensively reflect the expected value of the loss of the system in extreme cases with different probabilities, but the index proposed in this study is too single; Journal articles [8] studies the full time scale of the impact of extreme weather on the distribution network, and divides the time period for the distribution network to deal with extreme weather into pre event period, in-process period and post event period. However, only the short-term resilience index is considered, and the long-term resilience index is not considered; Journal articles [12] uses RI as the resilience evaluation index, which is defined as the amount of recovery divided by the recovery time. This index can take into account the amount of recovery and the recovery speed, but it can't reflect the resilience of the disaster and before the disasters. Journal articles [13] considered the impact of volcanic eruptions on the distribution network, and reasonably planned and optimized distributed energy to improve recovery.

At present, most resilience index framework only evaluate resilience from the structural level or system operation level [14], and can't comprehensively consider the level of disaster resilience on multiple time scales before, during and after disasters. Therefore, it is necessary to propose a framework of distribution network resilience evaluation system that can comprehensively consider multi-time scales and the generation grid load storage resources, distribution network structure and distribution network operation mode. This paper presents a framework considering the failure rate of internal equipment and the intensity of natural disasters in the distribution network, considering the two dimensions of time and generation grid load storage resources, and integrating the structural and operational levels of the distribution system. The resilience index framework includes three levels: prevention resilience, resistance resilience and recovery resilience.

2 Connotation of Resilient Distribution Network

The concept of resilience was first proposed by Holling CS in ecological research in 1973 to measure the ability of ecosystems to withstand and absorb disturbances and maintain system stability [15]. So far, there is no final definition of power system resilience in academia, but in the research, resilience is defined as the ability of power system to prevent, resist and quickly restore load for small probability high loss extreme events.

When the distribution system is faced with extreme natural disasters, most components will fail, resulting in a large area of power failure. When the distribution system breaks down, it will appear the state of derating operation and start to repair the faulty components, so that the distribution system will gradually return to the original normal operation state. Figure 1 shows the curve of the system status changing with time when the distribution system is affected by natural disasters [16]. Generally speaking, the power system status can be taken as the system load [17].

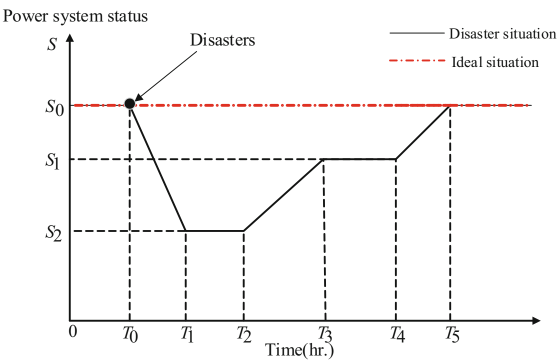

Fig. 1. State curve of power system under extreme natural disasters.

According to the disaster process, the state of distribution system can be divided into the following three stages [18]: pre disaster stage, in disaster stage and post disaster stage.

(1) Pre disaster prevention stage [0, T_0]: before extreme natural disasters, the system has been in normal operation. In this state, all system components are normal, and the state of the power system is also at the maximum level S_0. In this stage, the system can accurately predict the weather condition [19], strengthen the weak components and related lines, do a good job in basic response in advance, and improve the prevention ability of the distribution system to deal with natural disasters.
(2) In the disaster resistance stage [T_0, T_1]: after a natural disaster, a large number of components of the distribution system fail, some lines are disconnected, resulting in power loss of some users, the system functional state curve decreases[20], and the distribution system is in the derating operation state S_0. In this stage, the distributed energy can be controlled to realize the isolated island operation state of the microgrid and reduce the overall power loss of users.
(3) Post disaster recovery stage [T_1, T_5]: disaster recovery stage mainly includes emergency recovery state and continuous recovery state. Emergency recovery refers to the restoration of the state of the distribution system by taking measures such as network reconfiguration and configuration of mobile energy storage vehicles after the transit of extreme natural disasters. These measures can solve the power loss state to a certain extent, and make the state of the distribution system rise to state S_1; Continuous recovery refers to the maintenance and replacement of faulty components, so that all faults are eliminated, and the overall function curve of the distribution system is restored to the original state S_0.

3 Resilience Evaluation Index System and Evaluation Process

3.1 Resilience Index Evaluation System

In order to evaluate the system resilience more comprehensively, this paper considers the time and generation grid load storage resources at the same time. This paper proposes a distribution network resilient evaluation system that can comprehensively consider the multi time and generation grid load storage resources, as shown in Fig. 2.

The preventive resilience index can effectively describe the preventive ability of the distribution network to deal with disasters. The indicators at this level mainly include the cable ratio of lines, the proportion of heavy load lines, etc. Generally speaking, the higher the automation level of the distribution network, the better the health of its own equipment, the better the preventive resilience index; Resistance resilience can describe the ability of distribution network to cope with disasters without collapse. The indicators at this level mainly include load loss rate, load loss speed and other indicators. The indicators at this level are not only related to the intensity of natural disasters, but also related to the grid strength of the distribution network itself and the controllable resources of the distribution network. The better the resistance resilience index is, the stronger the disaster response ability of the distribution network is; Recovery resilience index describes the resilience of distribution network after disasters. This level index mainly includes load

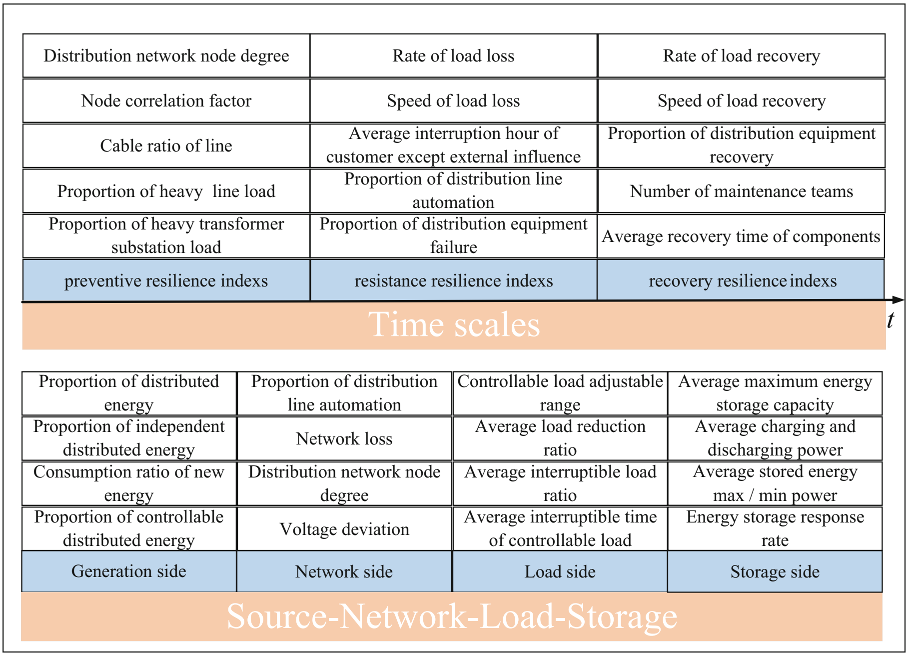

Fig. 2. Resilience index evaluation system.

recovery rate and load recovery speed. This level index can comprehensively evaluate the recovery resilience of distribution network after disasters. Recovery resilience index is mainly related to the recovery resources and recovery strategies of distribution network system. The more recovery resources, the more reasonable the recovery strategy, and the better the recovery resilience index. While considering the time scale, the resilience index of generation grid load storage is also taken into account. The generation grid load storage is described from the source side, load side, network side and storage side respectively.

In view of space limitations, this paper only gives the calculation method of some resilient indexes.

(1) Rate of load loss

The loss of load rate under disasters refers to that the distribution network cannot fully absorb the impact of disasters, resulting in the loss of power supply to some loads. The loss of load rate under disaster reflects the severity of damage to the distribution network after the disaster. The smaller the value, the stronger the disaster resistance of the distribution network itself.

$$R_{RLL} = \frac{\sum_{i=1}^{N} P_{load,i}^{loss}}{\sum_{i=1}^{N} P_{load,i}} \tag{1}$$

where, R_{RLL} is the load loss rate, $\sum_{i=1}^{N} P_{load,i}^{loss}$ represents the load loss of node i, and $\sum_{i=1}^{N} P_{load,i}$ represents the total load of node i.

(2) Speed of load loss

The speed of loss of load under disaster refers to the average speed of loss of load of distribution network from the pre disaster state to the post disaster state.

$$V_{SLL} = \frac{\sum_{i=1}^{N} P_{load,i}^{loss}}{T_e} \tag{2}$$

where, V_{SLL} is the speed of loss of load, $P_{load,i}^{loss}$ is the amount of loss of load, and N is the number of nodes in the distribution network.

(3) Distribution equipment failure ratio

The proportion of distribution equipment failure is the proportion of the numbers of faulty distribution equipment to the total numbers of equipment. This index can represent the strength of distribution network equipment under extreme natural disasters.

$$Ra_{fa} = \frac{N_{fa}}{N} \tag{3}$$

where, Ra_{fa} is the proportion of equipment failure, N_{fa} is the number of equipment failures, and N is the total numbers of equipment.

(4) Nodal degree

Node degree is an index used to describe the importance of a node in a complex network. The node degree index of a node is defined as the number of edges containing nodes. Generally speaking, the larger the node degree of a node, the more important the node is. If the node degree of a network as a whole is larger, it means that the network is more complex and the connection is more complex.

$$K = \sum_{i=1}^{N} k_i \tag{4}$$

where, k_i is the number of nodes of node i, N is the number of network nodes, and K is the total node degree of the network.

(5) Rate of load recovery

It refers to the proportion that some loads get power supply again after using some recovery means in the distribution network. The load recovery rate reflects the recovery capacity of the distribution network after damage. The larger the value, the stronger the recovery capacity of the distribution.

$$R_{RE} = \frac{\sum_{i=1}^{N} P_{load,i}^{re}}{\sum_{i=1}^{N} P_{load,i}} \tag{5}$$

where, R_{RE} is the load loss rate, $\sum_{i=1}^{N} P_{load,i}^{re}$ is the load recovery amount of node i, and $\sum_{i=1}^{N} P_{load,i}$ represents the total load of node i.

(6) Speed of load recovery

It refers to the speed at which the system recovers to normal operation during the load recovery phase. The speed of system recovery reflects the ability of distribution network to respond to disasters quickly.

$$V_{RSL} = \frac{1}{T}\sum\nolimits_{t_s=1}^{T_{re}}\sum\nolimits_{i=1}^{N} p_{re.t_s.i} \tag{6}$$

where, V_{RSL} is the load recovery speed; $p_{re.t_s.i}$ represents the load power recovered by the node i in the time period t_s.

(7) Distribution equipment recovery ratio

The proportion of distribution equipment recovery is the proportion of the number of recovery distribution equipment to the total numbers of equipment. This index can represent the strength of distribution network equipment under extreme natural disasters.

$$Ra_{RE} = \frac{N_{RE}}{N} \tag{7}$$

where, Ra_{RE} is the proportion of equipment failure, N_{RE} is the number of equipment failures, and N is the total numbers of equipment.

3.2 Resilience Assessment Process

The overall research idea of resilient evaluation integrates the construction of natural disaster model and the simulation analysis of distribution system, and constructs a resilient evaluation index framework that includes the influence factors of natural disasters and the factors of distribution equipment itself.

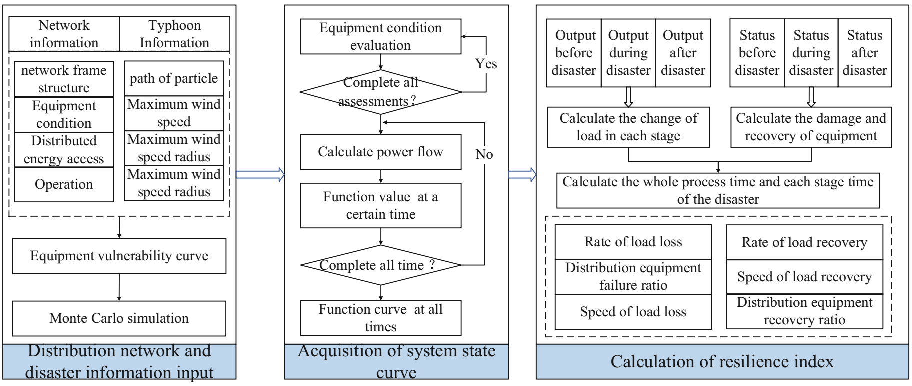

Fig. 3. Resilience assessment process.

Figure 3 shows the flow chart of the specific evaluation method of resilience, including the following steps:

Step1: The first part is the input of distribution network and disaster information. The distribution network information includes the network structure, equipment, distributed energy access and operation of the distribution network. The typhoon information includes the moving track of the typhoon, the maximum wind speed, the maximum wind speed radius, etc. Through the input of the above information, the failure probability of each component can be obtained, and the state of each component can be obtained through Monte Carlo simulation.

Step2: Using the obtained component states, the distribution network is simulated to obtain the state of the system at each time. Repeat the operation at each time to further obtain the system state values at all times, and finally obtain the system state curve.

Step3: According to the obtained system state curve, the system state value of each stage and the time of each stage are further obtained. Combined with the resilience evaluation index system constructed in Sect. 3.1, the resilience level of the system under the natural disaster is then calculated.

4 Case Study

This case takes the IEEE 33-node distribution system as test system. The IEEE 33-node distribution network system contains 33 nodes, with a total of 32 sectionalizing switches and 5 interconnection switches. The sectioning switches are closed under normal conditions, and the interconnection switches are disconnected under normal conditions (Fig. 4).

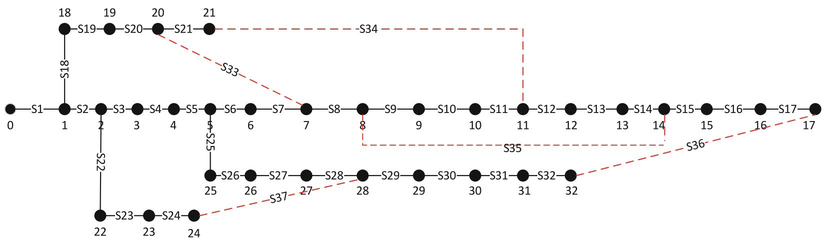

Fig. 4. IEEE 33-node test feeder.

Assuming that the typhoon lasts for eight hours, A total of three cases are considered. Case 1 has a greater impact of natural disasters, most lines fail, case 2 and case 3 have a smaller and consistent impact of natural disasters, and the fault lines are much less than case 1. The maintenance speed of case 1 and case 2 is 1 line each hour, and the maintenance speed of case 3 is 2 lines per hour. The maintenance sequence is in accordance with the fault sequence. The line fault conditions of the three cases are obtained through step 1 in Sect. 3.2, are shown in Table 1.

The load curve of normal and disaster conditions at eight times in three cases are shown in Fig. 5. The natural disaster in case 1 is more serious, and the disaster conditions in case 2 and case 3 are the same. Therefore, the number of fault lines in case 1 is more than that in case 2 and case 3, and the fault conditions in case 2 and case 3 are exactly

Table 1. Line fault at each time.

Time	Fault lines		
	Case1	Case2	Case3
11:00	6,11	None	None
12:00	9	32	32
13:00	24	29	29
14:00	19	None	None
15:00	15, 28	22	22
16:00	16	19	19
17:00	20	None	None
18:00	21	18	18
Repair time	1h/line	1 h/line	0.5 h/line

the same at each time. In all three cases, the typhoon lasted for a total of eight hours. During these eight hours, the system state curve continued to decline, and the overall load of the system continued to decrease. From the ninth hour, the fault line began to be repaired, the system state curve began to rise, and the overall load of the system also began to increase to the level before the natural disaster. When the fault line was completely repaired, the system state returned to the ideal state. To sum up, in the three cases in Fig. 5, the system state curve shows a state of first falling and then rising.

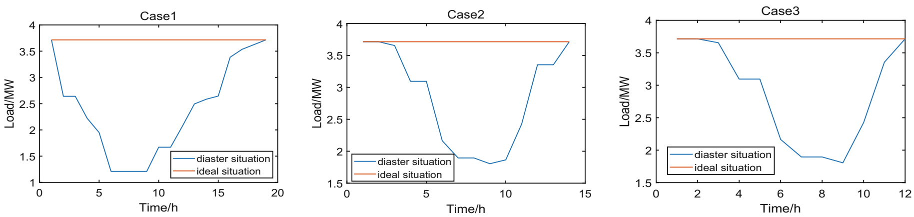

Fig. 5. System state curve of the whole process of disaster occurrence in three cases.

Through the system state curve of the distribution system during the disaster, the system resilience is evaluated by using some of the proposed resilience indexes. Using the formula mentioned in Sect. 3.1 to calculate the resilience index in three cases, and the obtained resilience index values in three cases are shown in Table 2.

According to the data in Table 2, the rate of load loss in case 1 is 67.43%, while the rate of load loss in case 2 and case 3 is 51.41%. The rate of load loss in case 1 is higher than that in case 2 and case 3, which is consistent with the situation of natural disasters. Because only the line repair speed is inconsistent in case 2 and case 3, they are the same in some resistance indicators. The repair speed of the faulty line in case 2 is less than that in case 3, Therefore, the index of case 3 is better than that of case 2 in terms of load

Table 2. Resilience index value.

Resilience index	Case1	Case2	Case3
Rate of load loss	67.43%	51.41%	51.41%
Speed of load loss (MW/h)	0.4175	0.2388	0.2388
Distribution equipment failure ratio	31.25%	15.63%	15.63%
Nodal degree	30.5	31.375	31.375
Rate of load recovery	100%	100%	100%
Speed of load recovery (MW/h)	0.2505	0.382	0.637
Distribution equipment recovery ratio	100%	100%	100%

recovery speed. For the repair rate of the overall fault line in the three cases, the situation is set to unlimited repair resources, so the repair rate can reach 100%. In general, since the natural disaster intensity of case 3 is small and the repair speed of the fault line is fast, the overall resilience index of case 3 is the best, while the natural disaster intensity of case 1 is large and the repair speed of the fault line has no advantage, so the overall resilience index of case 1 is the worst.

Therefore, from the analysis of the above results, it can be seen that the resilience index system proposed in this paper can effectively reflect the resilience level of the distribution system in dealing with natural disasters of different intensities. The resilience index system can also describe the resilience of prevention, resistance and recovery. Generally speaking, the higher the intensity of the distribution system, the lower the intensity of natural disasters, the better the indicators of preventive resilience and resistance resilience, the faster the system repair speed and the more repair resources, the better the indicators of system resilience. In general, the proposed resilience evaluation index system and evaluation method can basically achieve the resilience level of distribution system in extreme natural disasters, and can also provide some guidance for the improvement of resilience level.

5 Conclusion

This paper proposes a practical evaluation index framework of distribution network resilience to extreme disturbance events. The index system includes two dimensions: time and generation-grid-load-storage resources. The time dimension index framework covers three aspects: prevention stage, resistance stage and recovery stage, and the generation-grid-load-storage resources dimension index system covers four aspects of generation grid load storage. The evaluation index framework can scientifically evaluate the resilience of distribution network to disasters, and provide scientific reference and suggestions for distribution network planning and construction and operation and maintenance management. Future research can further refine the distribution network resources and include more resilience indicators, so as to establish a more perfect distribution network resilience index framework.

Acknowledgment. This research was supported by the Science and Technology Project of State Grid Zhejiang Electric Power Co., Ltd. (2022FD02).

References

1. Navarro-Espinosa, A., et al.: Improving distribution network resilience against earthquakes. In: IET International Conference on Resilience of Transmission and Distribution Networks (RTDN 2017), pp. 1–6 (2017). https://doi.org/10.1049/cp.2017.0339
2. Lu, C., Xiangyan, C., Jiping, A., Yuan, L., Zhiqiang, L., Weiyu, L.: Resilience evaluation of distribution network considering fault repair. In: 2021 China International Conference on Electricity Distribution (CICED), pp. 757–761 (2021). https://doi.org/10.1109/CICED50259.2021.9556794. (Author, F.: Contribution title. [C] // 9th International Proceedings on Proceedings. pp. 1–2. Publisher, Location (2010))
3. Park, J., et al.: Design for resilience in coupled industrial-ecological systems: Biofuels industry as a case study. In: Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology, p. 1 (2011). https://doi.org/10.1109/ISSST.2011.5936913
4. Oe, H., Yamaoka, Y.: A discussion of damage mitigation of natural disasters: How to increase citizens' preparedness. In: 2021 Third International Sustainability and Resilience Conference: Climate Change, pp. 18–22 (2021). https://doi.org/10.1109/IEEECONF53624.2021.9668124
5. Nickain, S.S.: Socio-economic resilience and the local background context: related variety matters. In: Nickain, Samaneh Sadat (ed.) Complexity and Resilience: Urban experiences in Southern Europe, pp. 125–156. River Publishers, New York (2022). https://doi.org/10.1201/9781003337645-5
6. Arefin, A.A., et al.: Power resilience enhancement of a pv-battery-diesel microgrid. In: 2020 International Conference on Smart Grids and Energy Systems (SGES), pp. 860–863 (2020). https://doi.org/10.1109/SGES51519.2020.00158
7. Teodorescu, H.L., Pickl, S.W.: Properties and use of a resilience index in disaster preparation and response. In: 2016 IEEE Symposium on Technologies for Homeland Security (HST), pp. 1–6 (2016). https://doi.org/10.1109/THS.2016.7568890
8. Wang, G.: Distribution System Preventive Dispatching Facing Extreme Weather Events and Its Application in Resilience Evaluation (2020). https://doi.org/10.27670/d.cnki.gcqdu.2020.003792
9. Peng, H., Wang, X., Wei, N., Li, S., Li, H.: Microgrid differentiated recovery operation for enhancing distribution system resilience. Power Syst. Technol. **45**(07), 2811–2821 (2021). https://doi.org/10.13335/j.1000-3673.pst.2020.2022
10. Du, S., Guo, C., Yu, X., Zhao, F., Xing, H., Fang, Y.: Review and prospect of resilient distribution network under typhoon disaster. Electric Power Autom. Equip. **42**(02), 176–186+209 (2022). https://doi.org/10.16081/j.epae.202110028
11. Li, Z., Zhao, B., Lin, D., Ni, C., Qin, Q., Han, B., Li, G.: Optimal allocation strategy of demand response for improving distribution network elasticity. Electric Power Autom. Equip. 1–9 (2022). https://doi.org/10.16081/j.epae.202204052
12. Mathew, R.K., Ashok, S., Kumaravel, S.: Resilience assessment using microgrids in radial distribution network. In: 2016 IEEE 7th Power India International Conference (PIICON), pp. 1–4 (2016). https://doi.org/10.1109/POWERI.2016.8077250
13. Saltos-Rodríguez, M., Aguirre-Velasco, M., Velásquez-Lozano, A., Ortiz-Villalba, D., Villamarín-Jácome, A.: Distributed generation for resilience enhancement on power distribution system against lahars occurrence after a volcanic eruption. In: 2021 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America), pp. 1–5 (2021). https://doi.org/10.1109/ISGTLatinAmerica52371.2021.9543008

14. Huang, W., Qian, T., Li, Z., Tang, W., Wu, Q.: A survey of resilience indexes in power systems. In: 2021 IEEE Sustainable Power and Energy Conference (iSPEC), pp. 1475–1480 (2021). https://doi.org/10.1109/iSPEC53008.2021.9735821
15. Holling, C.S.: Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. **4**, 1–23 (1973)
16. Bhusal, N., Abdelmalak, M., Kamruzzaman, M., Benidris, M.: Power system resilience: current practices, challenges, and future directions. IEEE Access **8**, 18064–18086 (2020). https://doi.org/10.1109/ACCESS.2020.2968586
17. Ti, B., Li, G., Zhou, M., Wang, J.: Resilience assessment and improvement for cyber-physical power systems under typhoon disasters. IEEE Trans. Smart Grid **13**(1), 783–794 (2022). https://doi.org/10.1109/TSG.2021.3114512
18. Gao, H., Chen, Y., Mei, S., Huang, S., Xu, Y.: Resilience-oriented pre-hurricane resource allocation in distribution systems considering electric buses. Proc. IEEE **105**(7), 1214–1233 (2017). https://doi.org/10.1109/JPROC.2017.2666548
19. Poudel, S., Dubey, A., Bose, A.: Risk-based probabilistic quantification of power distribution system operational resilience. IEEE Syst. J. **14**(3), 3506–3517 (2020). https://doi.org/10.1109/JSYST.2019.2940939
20. Bessani, M., et al.: Probabilistic assessment of power distribution systems resilience under extreme weather. IEEE Syst. J. **13**(2), 1747–1756 (2019). https://doi.org/10.1109/JSYST.2018.2853554