Vulnerability Assessment Method of Distribution Network Including Distributed Power and Energy Storage Access

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Abstract. With the access of distributed power and energy storage devices, the distribution network becomes more and more complex, and how to find the vulnerable nodes in the distribution network has attracted much attention. In this paper, a comprehensive vulnerability assessment method of distribution network is proposed from two aspects: structural vulnerability and state vulnerability. Structural vulnerability includes three evaluation indexes: improved node degree, improved node intermediate number and percentage of load loss. State vulnerability includes node voltage overlimit and line overload indicators. Through the improved IEEE33-node distribution network, the proposed vulnerability index is verified and analyzed, and the results show that the evaluation index proposed in this paper is consistent with the actual situation, which fully proves its rationality and effectiveness.

Keywords: Distribution network · Vulnerability assessment · Distributed power · Energy storage · Analytic hierarchy process

1 Introduction

With the access of distributed power and storage, distribution network becomes more and more complex, people pay more attention to the security of distribution network, and the vulnerability of distribution network gradually attracts the attention of scholars [1–3]. The so-called vulnerability of distribution network refers to the performance degradation, easy damage or instability of distribution system in the face of various external interference, failure or attack. Vulnerability is the weakness of the power distribution system in responding to abnormal situations, which may lead to system failure, power outage or other adverse consequences [4].

At present, some research work has been done on vulnerability assessment of power system. Based on the theoretical system of complex networks, literature [5] proposes a node vulnerability assessment method considering the characteristics of offshore oilfield power grid. Based on the historical fault analysis results, a node vulnerability assessment model of oilfield power system is established. Literature [6] considers that the traditional

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vulnerability assessment model does not combine the unique topology of the power grid, and the centrality index of the general complex network theory will be biased when it is used to assess the power grid vulnerability. Therefore, based on electrical parameters, the centrality index is redefined and a set of redefined centrality index is proposed. The above literatures all propose a set of vulnerability assessment methods for power grids, but do not take into account the case of distributed power access in the distribution network. Literature [7–9] all considered the situation of distributed photovoltaic access in the distribution network, and proposed a node vulnerability index assessment method that took into account the volatility of new energy power output. Literature [10] proposes a vulnerability analysis and quantitative assessment method for power grids including wind power access to analyze the influence of different wind speeds and different access locations on line vulnerability and the variation of line vulnerability.

However, most of the above methods only assess the vulnerability of nodes with distributed power access, and there is no energy storage access in the distribution network studied, and no method is proposed to assess the vulnerability of all nodes in the distribution network.

In view of the shortcomings of existing studies, this paper puts forward a set of comprehensive vulnerability assessment indexes for distribution network nodes from two aspects: structural vulnerability and state vulnerability, considering that distribution network has distributed power supply and energy storage access and its radiation state.

2 Vulnerability Index of Distribution Network

2.1 Structural Vulnerability Index

In view of the radial topology of the distribution network, combined with the node access load, the size of the distributed power supply and the charging and discharging capacity of the energy storage device, this paper improves the index of node degree and intermediate number in the complex network theory, and puts forward the index of load loss percentage to obtain the vulnerability index of the distribution network structure.

(1) Improved node degree indicator.

Considering that the load or power of the distributed power supply connected to each node in the distribution network are not the same, this paper adjusts the weight of the number of degrees in the number of nodes based on the size of the node's load or distributed power supply, and considers not only the number of nodes connected to the node, but also the size of the load or distributed power supply of the node and all the nodes connected to it. Therefore, an improved node degree index is proposed. The expression is

$$D_i' = \frac{1}{S_{\max}} \sum_{j \in M_d} (D_j \sqrt{S_i S_j}) \tag{1}$$

$S_{i/j}$ is a measure of node i/ node j load or distributed power output size index.This paper takes its access capacity instead. M_d is the set of all nodes connected to node i. D_j is the degree of node j connected to node i. $S_{\max}$ is the maximum load or capacity of the distributed power supply in all nodes.

(2) Improved node number index.

The distribution network discussed in this paper has distributed power supply and energy storage device access, so there are three types of nodes, load node, power node and energy storage node. The nodes connected to the energy storage device have two characteristics. In this paper, nodes are divided into source nodes and load nodes according to the characteristics of source and load, in which the nodes connected to the energy storage device can be used as both source nodes and load nodes.

In the distribution network, the overall flow of energy flows from the source node to the load node. Therefore, this paper considers the intermediary times of the shortest path between all source-load node pairs in the distribution network as a reference for improving node interlocutors, and improves the node interlocutors index. The expression is as follows

$$B_{k'} = \sum_{\substack{i \in M_s, \\ j \in M_l, \\ s \in M_e}} \frac{S_i S_j}{S_i + S_j} M_{k1} + \frac{1}{2}(\frac{S_i S_s}{S_i + S_s} M_{k2} + \frac{S_s S_j}{S_s + S_j} M_{k3}) \tag{2}$$

M_s is a collection of all distributed power supply nodes. M_e is a collection of all energy storage nodes. M_l is a collection of all load nodes. The load node of the shortest path corresponding to the distributed power node i is node j. M_k is the comparison function of whether the shortest path of two nodes passes through node k. If the shortest path passes through node k, its value is 1, and if the shortest path passes through node k, it is 0.

(3) Percentage loss of load.

When a permanent fault occurs in the power grid, the faulty node will have a certain load loss, and the nodes in the downlink area may also lose part of the load because they fail to transfer power in time. When the nodes in the line area have distributed power supply or energy storage access, the power outage range can be reduced to a certain extent, so the expression of load loss percentage is

$$L_q = \sum_{q \in M_q} p_q \frac{\Delta S_q^{loss} - \Delta S_q^s - \Delta S_q^e}{S_N} \tag{3}$$

M_q is the set of states of the lost node q and the line between it and the previous node. p_q is the probability of state q occurring. ΔS_q^{loss} is the total amount of load lost by running state q. ΔS_q^s is the power that the nearby DG independently sends to the non-fault point in the fault area. ΔS_q^e is the power that the nearby energy storage device sends independently to the non-fault point in the fault area. S_N is the load power of the grid.

2.2 State Vulnerability Index

(1) Node voltage over threshold indicator.

The overvoltage of distribution network nodes may cause equipment damage and power quality problems, increase the vulnerability of the system, increase the risk of power outage, and affect the normal operation of the distribution network. The expression of the degree to which the node voltage exceeds the limit is

$$V_{ri,t} = \begin{cases} \frac{|V_{i,t}-1|}{\delta} & |V_{i,t} - 1| > \delta \\ 0 & |V_{i,t} - 1| \leq \delta \end{cases} \tag{4}$$

$V_{ri,t}$ is the threshold of node i voltage at time t. $V_{i,t}$ is the unit value of node i voltage at time t. $\pm\delta$ is the per unit value of the voltage offset specified by the normal operation of the line.

(2) Line overload indicator.

By analogy with the node voltage overlimit index, the harm of line overload is also related to the degree of line overload and the importance of the line, and the expression of the degree of line overload is

$$P_{rq,t} = \begin{cases} \frac{P_{q,t}-\xi}{1-\xi} & P_{q,t} > \xi \\ 0 & P_{q,t} \leq \xi \end{cases} \tag{5}$$

$P_{q,t}$ is the ratio of the actual power on the line at time t to the rated power. ξ is the ratio of the maximum power to the rated power that does not cause the risk of line overload.

3 Establishment of Comprehensive Vulnerability Index

In order to determine the weight of each index, this paper adopts analytic hierarchy process to determine the weight of each index. When considering the structural vulnerability, the index of improving the number of degrees of nodes and the index of improving the number of nodes are equally important in this report, while the index of percentage of load loss is slightly more important than the two, so the comparison matrix can be obtained as $\begin{bmatrix} 1 & 1 & 1/3 \\ 1 & 1 & 1/3 \\ 3 & 3 & 1 \end{bmatrix}$. When state vulnerability is considered, this report considers that the node voltage overlimit index and line overload index are equally important, so the comparison matrix can be obtained as follows $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$. For structural vulnerability, the weights of improved node degree index, improved node intermediate number index and percentage of load loss index are 0.2, 0.2 and 0.6, respectively. For state vulnerability, the weights of node voltage overlimit indicator and line overload indicator are 0.5 and 0.5, respectively. Table 1 shows the weight value of each indicator after summary.

Table 1. Weight values of each indicator.

Index	D'_i	B'_i	L_i	V_{ri}	P_{ri}
Weight coefficient	0.2	0.2	0.6	0.5	0.5

Structural vulnerability index and state vulnerability index can be expressed as

$$V_i^I = (0.2D_i' + 0.2B_i' + 0.6L_i) \tag{6}$$

$$V_i^{II} = (0.5V_{ri} + 0.5P_{ri}) \tag{7}$$

V_i^I and V_i^{II} are the structural vulnerability index and state vulnerability index of node i respectively.

The comprehensive vulnerability index is the synthesis of structural vulnerability index and state vulnerability index, which can be expressed as

$$\overline{V}_i = (\omega_1 V_i^I + \omega_2 V_i^{II}) \tag{8}$$

$\overline{V}_i$ is the comprehensive vulnerability indicator of node i. ω_1 and ω_2 are the weight coefficients of structural vulnerability index and state vulnerability index of node i respectively in the comprehensive vulnerability index.

4 Example Analysis

4.1 Example Setting

In this paper, IEEE 33 node distribution network system is used for example verification. Since there is no distributed power supply and energy storage device access in the traditional IEEE33 node, this paper makes some improvements on the basis of the traditional IEEE33 node, and adds six distributed power supplies, namely access node 7, node 10, node 13, node 26, node 30 and node 33, all of which use fixed power factor to generate electricity. The power factor is identical to 0.95. An energy storage device, access node 18, with rated power of 100kW and rated capacity of 1MW•h is added. The improved IEEE33-node power distribution system is shown in Fig. 1.

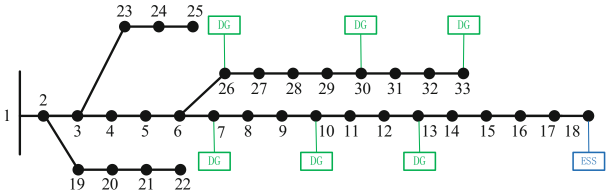

Fig. 1. Improved IEEE33 node distribution system.

Table 2 lists the capacity of the distributed power supply connected to each node.

The typical daily load and the normalized output curve of photovoltaic used in the calculation example, as well as the change of the state of charge of the energy storage device, are shown in Fig. 2.

Table 2. Distributed power supply capacity connected.

Access node	7	10	13	26	30	33
Capacity /kW	200	100	100	100	100	100

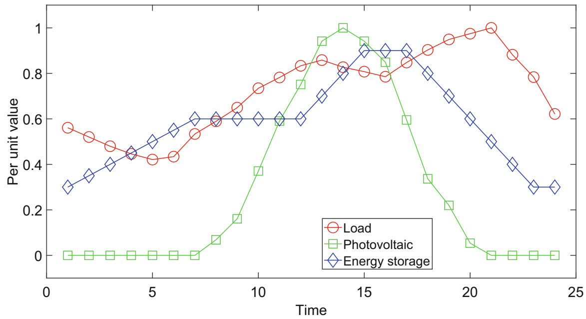

Fig. 2. Normalization curves of load, photovoltaic, and energy storage changes.

4.2 Result Analysis

(1) Structural vulnerability index.

From the perspective of improving node degree index, the top five nodes with greater vulnerability are node 24, node 25, node 7, node 3 and node 8, while the top five nodes with less vulnerability are node 18, node 22, node 17, node 16 and node 11. Among them, nodes 24, 25 and 7 are vulnerable because they are connected to a large load and distributed power supply respectively, and node 24 and node 7 are located in the middle of the line. The reason why node 3 and node 8 are vulnerable is that they are in the middle of the line, especially node 3 is located at the "fork" and there are more than two nodes connected to it, so it is particularly important in the system. Among the top 5 nodes with low vulnerability, 4 nodes are at the end (first) of the distribution network line, and the connectivity on the line is not strong, and the load or distributed power supply connected is small, so the vulnerability is small.

From the perspective of improving node number index, the top five nodes with greater vulnerability are node 6, node 26, node 27, node 28 and node 7, while the top five nodes with less vulnerability are node 18, node 22, node 25, node 24 and node 21. This indicator is highly correlated with the number of mediations of the shortest path between the node as a pair of source charged nodes. In particular, node 6, located at the intersection of two distributed power supply branches, has 146 intermediary times, accounting for more than 68% of all source load node pairs. The location is very critical, and the intermediary is the best, so the vulnerability is the greatest. The order of the index of the number of nodes including the source load node pairs is roughly the same as the order of the mediating times as the shortest path between all node pairs, only the order of individual nodes is slightly different.

From the perspective of load loss percentage index, the top five nodes with greater vulnerability are node 1, node 2, node 3, node 23 and node 24, among which nodes 1, node 2 and node 3 are the three nodes closest to the root node in the distribution network of IEEE33 nodes, so the load loss percentage index is larger. On the branch of node 23 and node 24, although there are fewer nodes, the load is heavier, so the percentage of load loss index of node 23 and node 24 is greater than that of node 4. The top five nodes with low vulnerability are node 33, Node 18, node 22, node 17, and node 16. These nodes are far away from the root node and suffer less load after failure. Therefore, they are less vulnerable. From the overall trend, the closer each node is to the root node, the greater the percentage of load loss and the greater the vulnerability of the node. From the specific sorting point of view, the load loss percentage of each node is also related to the access load of all nodes from this node to the end of the branch, and the higher the access load will change the ranking of the node's load loss percentage.

From the above analysis, it can be seen that the size of the structural vulnerability indicators proposed in this report are consistent with the actual situation of the distribution network.

(2) State vulnerability index.

From the point of view of node voltage overtripping, the top five nodes with greater risk of overtripping are node 17, node 18, node 32, node 33 and node 16. The common feature of these nodes is that most of them are located in the end part of the distribution network line, and the distance to the root node of the station area is far, so the voltage value is low, and there is a risk of exceeding the lower limit. Node 18 is farther away from the first end than node 17, but its exceedance is slightly better than node 17. This is because the voltage overlimit situation is improved after the energy storage device is connected, but the node voltage overlimit risk is still high, and the optimal scheduling strategy of the energy storage device needs to be further optimized.

From the Angle of line overload analysis, the top five nodes with greater risk of over-limit are node 1, node 2, node 3, node 4 and node 5. The common feature of these nodes is that they are located at the first end of the line, and almost all the load power flows through the line of these nodes, so the risk of line overload is greater.

From the above analysis, it can be seen that the state vulnerability indicators proposed in this report are consistent with the actual situation of the distribution network.

(3) Comprehensive vulnerability.

According to the method proposed in this paper, the comprehensive vulnerability index of each node is calculated, as shown in Fig. 3.

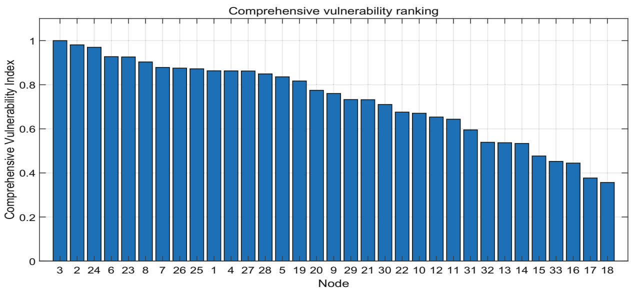

Fig. 3. Ranking of comprehensive vulnerability indicators.

5 Conclusion

In this paper, a comprehensive vulnerability assessment method of distribution network is proposed from two aspects: structural vulnerability and state vulnerability. In order to comprehensively assess the vulnerability of each node in the distribution network, this paper uses analytic hierarchy process to assign weights to each index, and then obtains the comprehensive vulnerability assessment results of each node. Through the improved IEEE33-node distribution network, the proposed vulnerability index is verified and analyzed, and the results show that the evaluation index proposed in this paper is consistent with the actual situation, which fully proves its rationality and effectiveness.

References

1. Li, S., Luo, C., Wu, H., et al.: Node vulnerability assessment of active distribution network accounting for topological structure, operational characteristics. Sustain. Energy Technol. Assess. 64103675 (2024)
2. Xiaowei, W., Qiankun, K., Liang, G., et al.: Economic evaluation for 5G planning of distribution network considering transmission loss and vulnerability. Sustain. Energy Grids Netw. **36** (2023)
3. Pan, L., Feng, W., Teng, M., et al.: Two-stage cooperative real-time autonomy control strategy considering vulnerability of active distribution networks. Renew. Energy **219**(P1) (2023)
4. Shiwei, L., Hongbin, W., Xiaodong, Y., et al.: Node vulnerability-aware co-deployment of D-PMUs and FTUs for active distribution networks. Int. J. Elec. Power Energy Syst. **55**(PA) (2024)
5. Hui, R., Zhibin, Z., Kai, J.: Node vulnerability evaluation of offshore oilfields power system. Elec. Power Sci. Eng. **38**(02), 18–27 (2022). (in Chinese)
6. Shaonan, C., Shuo, L., Shan, L., et al.: Power grid vulnerability evaluation based on electrical centrality indicators. Distrib. Util. **38**(08), 70–76 (2021). (in Chinese)
7. Junzhao, C., Tao, L., Hui, D.: State vulnerability assessment considering the output fluctuation of new energy power supply nodes. Elec. Measure. Instrum. **38**(08), 70–76 (2021). (in Chinese)
8. Hao, G., Liang, T., Wenqi, W., et al.: Researchon vulnerability assessment of distribution network in accessing distributed photovoltai. Microcomput. Appl. **40**(04), 112–115 (2024). (in Chinese)
9. Zixin, W., Shihong, M., Shuyu, G., et al.: Node vulnerability evaluation of distribution network considering randomness characteristic of distributed generation output. Elec. Power Autom. Equip. **40**(04), 112–115 (2024). (in Chinese)
10. Xiaogan, H., Yanhui, Z., Bochao, Y., et al.: Vulnerability analysis and quantitative assessment of power systems with wind power. Power Capacitor React. Power Compens. **44**(06), 108–116 (2023). (in Chinese)