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Research on Load State Sensing and Early Warning Method of Distribution Network under High Penetration Distributed Generation Access

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Abstract: Aiming at the problems of power flow fluctuation and voltage exceeding standard caused by high permeability distributed power supply access, this paper proposes a load state perception early warning method for distribution networks. Firstly, the random behavior characteristics and voltage early warning mechanisms of power supply and load in distribution networks are analyzed, the dynamic model of distribution networks based on complex network theory is established, and the risk index of voltage exceeding limits under the conditions of high permeability distributed power supply access is put forward. Secondly, the random power flow of distribution networks based on the Monte Carlo method is studied by sampling and analyzing the dynamic model of distribution networks. Then, the risk calculation and safety assessment of voltage exceeding limits are carried out on the currently extracted model, and the risk control strategy of distribution network operation is put forward. Finally, an improved IEEE30-node distribution network topology is proposed. Through simulation analysis, it is proven that the load situation awareness early warning method of distribution networks can effectively predict, improve the security of distribution networks, and provide timely early warning information for maintenance personnel.

Keywords: distributed power supply; load flow analysis; new energy; power system

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1. Introduction

The goal of "double carbon" has accelerated the process of green and low-carbon transformation in China. The new power system based on high-permeability distributed generation will be the new development direction in the future [1–4]. High-permeability distributed power generation is to connect a high proportion of renewable energy power generation equipment to the new power system, and at the same time connect a large number of power electronic components with nonlinear characteristics. Renewable energy power generation is characterized by high randomness and uncertainty. Power electronic equipment lacks the inertial support of synchronous generators, which leads to the risk of voltage exceeding limits and brings great challenges to the operation, maintenance, and overhaul of distribution networks [5–8]. In order to meet the above challenges, it is urgent to study a new method of load situation awareness and early warning in distribution networks to deal with the power flow fluctuation caused by high penetration distributed generation access.

Power flow calculation is of great significance for analyzing the active power flow, voltage distribution and network loss of distribution networks. Compared with the traditional distribution network, the access of high-permeability distributed power supply will bring greater volatility. Because the power flow has the characteristics of bidirectional flow, it is necessary to access a high proportion of power electronic equipment. Power flow analysis needs to classify distributed nodes based on the stochastic model of power flow. A lot of research has been conducted on the analysis and calculation of power flow at home and abroad. The ref. [9] adopts the traditional Newton method to deal with the power flow problem of distribution networks with distributed power supply access. In the iterative process, various nodes are transformed into PQ nodes or PV nodes for calculation, which solves the three-phase power flow calculation problem of multi-type distributed distribution networks. The ref. [10] analyzes the operation characteristics of different types of distributed power sources, and treats them as different types of nodes, which improves the accuracy of power flow calculation but does not consider the randomness of power flow brought by distributed power sources. However, most of the above-mentioned research on power flow calculation focuses on deterministic analysis, and there is little research on stochastic power flow analysis.

At present, some scholars have carried out detailed research on the operation state of distribution network lines. The ref. [11] puts forward the index of power line weight, and studies the internal relationship between distribution network grid structure and complex network theory. It can accurately locate the fragile power lines, thus effectively improving the identification accuracy of distribution network node vulnerability. The ref. [12] puts forward a method to calculate the average distance of weighted power grids, and establishes the risk assessment index of power grid operation based on line loss rate and transmission efficiency drop rate. According to the load dynamics of nodes, the corresponding cascading failure model is established, which provides a reference for security constraints in optimal scheduling. The ref. [13] analyzes the power flow distribution mechanism under the cascading failure of distribution networks and puts forward the electrical coupling strength index to judge the connection relationships of nodes. At the same time, it establishes a node feature identification model based on electrical coupling strength, and compares it with traditional topological indexes. According to the dynamic change of power flow and the priority index of nodes, the ref. [14] puts forward a method to select the optimal access location of distributed generation. The ref. [15] takes the European power grid as an example, analyzes typical power outage accidents and their causes, and puts forward a fast recovery strategy based on A* algorithm, which is verified in IEEE-39 and IEEE-68 systems. The above references are all based on the power flow idea of power systema to study the deviation degree of voltage and power. It establishes the corresponding power grid vulnerability assessment index, and puts forward the rapid recovery strategy, which provides the theoretical research basis for this paper.

In recent years, most scholars are keen to study the problem of load state perception under the condition of large-scale distributed power supply access. The ref. [16] takes the Greek pilot project as an example, puts forward a new state estimation method of transmission and distribution system, and solves the application problem of integrated monitoring systems to deal with the uncertainty of power grids. The ref. [17] puts forward a power quality evaluation method based on data envelopment analysis, and establishes a power quality evaluation index system suitable for distributed generation. The ref. [18] puts forward a distributed generation access method based on the healthy power quality of distribution networks. At the same time, by selecting the comprehensive index to measure the power quality, the health state characteristic quantity is established. The ref. [19] puts forward an active distribution network operation risk assessment and early warning method based on graph theory, which uses multi-scenario analysis technology to improve the accuracy of state perception and calculation efficiency. The ref. [20] considers the start-up capability constraint of distributed generation, and selects the recovery path of distribution systems under black start according to the load weight and node importance, thus improving the flexibility of distribution networks under power failure. The above method does not make a hierarchical access scheme for the power grid based on vulnerability. With the diversification of access subjects of distribution networks, it is more difficult to study the flexible load of renewable energy supply and consumption demand, new energy vehicles, and various energy storage systems.

In this paper, nodes are classified based on graph theory to identify the location of vulnerable nodes, and then a state awareness method with risk assessment and early warning functions is developed. The simulation results show that the optimal access node of DG can be selected effectively.

Based on the research of the above problems, according to the relationship between the operation risk of a high-permeability distributed power supply connected to a distribution network and node criticality, this paper puts forward a voltage limit sensing early warning method for distribution networks. Firstly, the set of nodes and edges of distribution networks are described in the form of graph theory, and the behavior characteristics of distribution networks are analyzed. By establishing the dynamic model of distribution networks, the expected risk degree is quantified. Secondly, the probability distribution model of the stochastic process of distributed generation and load demand is established by the nonparametric kernel density estimation method, and the power flow characteristics of distribution networks under stochastic conditions are analyzed. Then, a dynamic optimization strategy considering the operation risk of distribution networks under load state is proposed, taking the minimum amount of abandoned electricity generated by renewable energy as the optimization goal, and combining the optimization adjustment of reactive power compensation equipment, the adjustment of distributed power factor, and the reduction of active output of distributed power supply. This strategy solves the problem of voltage overrun in distribution networks through reactive power compensation and active power reduction. Finally, based on the improved IEEE30-node, the proposed method is compared and simulated in the distribution network system. Practice has proven that the load situation awareness early warning method proposed in this paper can effectively predict the security of distribution networks, and provide effective theoretical support for the risk assessment and early warning method formulation of distribution networks.

2. Dynamic Model of Distribution Network Based on Graph Theory

According to one reference [21], there is no significant correlation between the complexity of the network model structure and the analysis accuracy of power flow distribution in distribution networks. Compared with the existing complex network model structure, describing the edge set and node set of distribution networks in the form of graph theory can dig out the physical information relationship in the characteristic parameters of distribution networks more quickly and accurately. On this basis, by analyzing the weights of each side, the running state and physical characteristics of the distribution network can be intuitively and accurately reflected. According to the physical model with distributed generation, it is defined as an undirected weighted graph $G = (P, L)$. Among them, the edge set can be expressed as $L = \{l_1, l_2, \cdots, l_n\}$. Distributed power supply, substation, and load are nodes of the network. The node set can be represented by $P = \{p_1, p_2, \cdots, p_m\}$.

The power flow distribution is used to judge the running state of the distribution network, and the electrical betweenness of the lines is calculated and weighted, thus establishing a weighted topological dynamic model [22]. The electrical betweenness is:

$$C_t(L_{p_i p_j}) = \frac{1}{P_t} \sum_{p_i \in A} \sum_{p_j \in B} \sqrt{S_{p_i} S_{p_j}} \left| I_{p_i p_j} \right| \tag{1}$$

where A is the set of distributed generation nodes; B is a collection of multiple types of load side nodes of the distribution network; P_i and P_j are both corresponding node pairs; S_{p_i} and S_{p_j} are the actual powers of nodes v_i and v_j respectively; $I_{p_i p_j}$ is the current generated between the node pairs; and P_t is the input power of the node.

In the process of analyzing the node state, in order to quantify the influence on the network topology when the nodes in the network quit due to faults, the method proposed in reference [23] is adopted to define the average connectivity index of the network as:

$$D_{v_i} = \frac{1}{N(N-1)} \sum_{i=1}^{N} C_i \tag{2}$$

$$C_i = \frac{1}{\sum_{j=1}^{N} W_{ij}} \tag{3}$$

$$W_i = Z_{ij} = \frac{U_{ij}}{I_i} \tag{4}$$

where N is the number of nodes; C_i is the reciprocal of the sum of the electrical distances between nodes; and W_{ij} is the electrical distance between nodes. When the nodes are in a fault state, the path is interrupted, and the length is equivalent to infinity. Namely $W_i = \infty$, and $C_i = 0$; Z_{ij} is the equivalent impedance between nodes, that is, the ratio of the road voltage U_{ij} between nodes to the node current I_i.

It can be seen from the above formula that D_{v_i} is directly proportional to the connectivity of the distribution network, that is, the more stable the grid structure is. When the node v_i exits, the stability change index of the distribution network structure is:

$$\overline{D}_{v_i} = \frac{|D_{v_i} - D_0|}{D_0} \mathrm{z} \tag{5}$$

where $\overline{D}_{v_i}$ stands for the strength of structural stability of the distribution network. The intensity is proportional to the influence of the node stop operation on the structural stability of the distribution network.

3. Distribution Network Operation Risk Index

3.1. Out-of-Limit Probability Index

In order to quantify the probability of out-of-gauge risk, reference [24] puts forward the index of out-of-gauge probability:

$$P_{vi} = \frac{N_{vi}}{N} \tag{6}$$

where N_{vi} is the sampling times of out-of-limit behavior; N is the total number of samples.

3.2. Risk of Voltage Overrun

The voltage over-limit risk is mainly concentrated in two aspects: node and system. The proposed voltage over-limit risk index is:

$$C_{Vvi,i} = P_{Vvi,i} \frac{\Delta V_{\mathrm{ave},i} + \Delta V_{\mathrm{max},i}}{2} \tag{7}$$

$$C_{\mathrm{V}vi,s} = \frac{1}{N_{\mathrm{nod}}} \sum_{i=1}^{N_{\mathrm{nod}}} C_{Vvi,i} \tag{8}$$

$$P_{\mathrm{Vvi},i} = \frac{N_{Vvi,i}}{N} \tag{9}$$

$$\Delta V_{\mathrm{ave},i} = \frac{1}{N_{Vvi,i}} \sum_{k=1}^{N_{Vvi,i}} \left| V_{i,k} - V_{\mathrm{lim},i} \right| \tag{10}$$

$$\Delta V_{\mathrm{max},i} = \max \left| V_{i,k} - V_{\mathrm{lim},i} \right| \tag{11}$$

where $C_{Vvi,i}$ is the exceeding index; $P_{Vvi,i}$ is the exceeding probability of v; $\Delta V_{\mathrm{ave},i}$ is the average value of the exceeding index level; $\Delta V_{\mathrm{max},i}$ is the upper limit of the exceeding index limit level; $C_{Vvi,s}$ is the exceeding index of the system; $N_{Vvi,i}$ is the number of overruns drawn; $V_{i,k}$ is the node voltage value in the kth sampling; and $V_{\mathrm{lim},i}$ is the maximum value of voltage.

3.3. Risk of Power Overrun

In this paper, the power limit risk index is proposed to quantify the power limit risk. The risk of power overrun index is concentrated in branches and systems, which can be expressed as:

$$C_{Svi,j} = P_{Svi,j} \frac{\Delta S_{\text{ave},j} + \Delta S_{\text{max},j}}{2} \tag{12}$$

$$C_{Svi,s} = \frac{1}{N_{\text{br}}} \sum_{j=1}^{N_{\text{br}}} C_{Svi,j} \tag{13}$$

$$P_{Svi,j} = \frac{N_{Svi,j}}{N} \tag{14}$$

$$\Delta S_{\text{ave},j} = \frac{1}{N_{Svi,j}} \sum_{k=1}^{N_{Svi,j}} \left(S_{j,k} - S_{\text{max},j} \right) \tag{15}$$

$$\Delta S_{\text{max},j} = \max\left(S_{j,k} - S_{\text{max},j} \right) \tag{16}$$

where $C_{Svi,j}$ is the out-of-limit indicator; $P_{Svi,j}$ is the probability of exceeding the limit of branch j; $\Delta S_{\text{ave},j}$ is the average power over-limit level of branch j; $C_{Svi,s}$ is the out-of-limit indicator of the system; N_{br} is the number of branches; $N_{Svi,j}$ is the excess number of sampling branches; $S_{j,k}$ is the apparent power when it exceeds the limit value by k times; and $S_{\text{max},j}$ is the rated capacity.

4. Random Power Flow Analysis Based on the Monte Carlo Method

In general, the output power of each power supply in the network is fixed. Therefore, it needs to use a deterministic calculation method for forward and reverse power generation. This method has good convergence and computational efficiency for a single radial network structure [24]. However, in the case of wind energy and photovoltaic power generation, the traditional methods have certain limitations. The Monte Carlo method can generate random data, which is a good simulation of intermittent energy output.

According to the research route of the Monte Carlo method, in order to meet the large data requirements of stochastic power flow analysis, the probability distribution model of stochastic process should be established first. Then, sample experiments are carried out to calculate the statistical characteristics of the parameters to be solved. Finally, the approximate value of the solution is given, and the probability distribution model of source charge is established by the nonparametric kernel density estimation method. This method does not contain any subjective factors and settings, and fully excavates the probability characteristics of the data itself.

The wind speed characteristics mainly obey the Weibull distribution, namely:

$$f(v) = \frac{a}{b} \left(\frac{v}{b} \right)^{a-1} \exp\left[-\left(\frac{v}{b} \right)^{a} \right] \tag{17}$$

$$k = \left(\frac{\sigma}{u} \right)^{-1.086} \tag{18}$$

$$C = \frac{\mu}{\gamma\left(1 + \frac{1}{a} \right)} \tag{19}$$

where v is speed; a is the distribution state factor; b is the distribution scale factor; σ is standard deviation; and γ is Gamma function.

The output power is:

$$P_{\mathrm{W}} = \begin{cases} 0 & v_{\mathrm{c0}} < v \leq v_{\mathrm{c1}} \\ a_1 v + a_2 & v_{\mathrm{c1}} < v \leq v_{\mathrm{t}} \\ P_s & v_{\mathrm{t}} < v \leq v_{\mathrm{c0}} \end{cases} \tag{20}$$

where P_s is the rated power; v_{c1} is the starting speed; v_{c0} is the cut out speed; v_{t} is rated wind speed; $a_1 = P_t/(v_{\mathrm{t}} - v_{\mathrm{c1}})$; and $a_2 = -a_1 v_{c1}$.

The probability function of wind power output is:

$$f(P_{\mathrm{W}}) = \frac{a}{a_1 b}\left(\frac{P_{\mathrm{W}} - a_2}{a_1 b}\right) \exp\left[\left(\frac{P_{\mathrm{W}} - a_2}{a_1 b}\right)^a\right] \tag{21}$$

Maximum frequency tracking method is adoped to study the power of photovoltaic generation, which is:

$$P_{\mathrm{PV}} = \varphi S_{\mathrm{c}} I_\alpha = \varphi S_{\mathrm{c}}(\kappa T - \kappa^2 T') \tag{22}$$

where S_{c} is the effective area of the photovoltaic panel; κ is air clarity coefficient; α is the inclination angle of the photovoltaic array; and T is affected by parameters such as the inclination angle of the PV array, ground reflectivity, and latitude.

When $T > 0$ and $T' < 0$, if $P_{\mathrm{PV}} \in [0, P_{\mathrm{PV}}(\kappa_{\mathrm{u}})]$, then the photovoltaic output probability density function is:

$$f_{P_{\mathrm{PV}}}(P_{\mathrm{PV}}) = \frac{C\left(\kappa_{\mathrm{u}} - \frac{1}{2}(\alpha + \alpha')\right)}{-\kappa_{\mathrm{u}} \varphi S_{\mathrm{c}} T' \alpha'} \mathrm{e}^{\frac{\lambda}{2}(\alpha + \alpha')} \tag{23}$$

where κ_{u} is the upper limit of the air clarity coefficient; and C and λ are both probability density functions of the air clearness coefficient.

Meanwhile, if $P_{\mathrm{PV}} \notin [0, P_{\mathrm{PV}}(\kappa_{\mathrm{u}})]$, then $f_{P_{\mathrm{PV}}}(P_{\mathrm{PV}}) = 0$.

When $T > 0$ and $T' > 0$, if $P_{\mathrm{PV}} \in [0, P_{\mathrm{PV}}(\kappa_{\mathrm{u}})]$, then the photovoltaic output probability density function is:

$$f_{P_{\mathrm{PV}}}(P_{\mathrm{PV}}) = \frac{C\left(\kappa_{\mathrm{u}} - \frac{1}{2}(\alpha - \alpha')\right)}{\kappa_{\mathrm{u}} \varphi S_{\mathrm{c}} T' \alpha'} \mathrm{e}^{\frac{\lambda}{2}(\alpha - \alpha')} \tag{24}$$

The probability function of the load adopts a normal distribution, which is:

$$f_{P_{\mathrm{L}}}(P_{\mathrm{L}}) = \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{\frac{-(P_{\mathrm{L}} - \overline{P}_{\mathrm{L}})^2}{2\sigma^2}} \tag{25}$$

where $\overline{P}_{\mathrm{L}}$ is the average load value; σ is the variance.

5. Dynamic Optimization Strategy for Load State Aware Operation Risk of Distribution Networks

Load state perception is to realize the state monitoring and operation decision of distributed power supply and distribution network equipment through the analysis and calculation of real-time measurement data. By optimizing the power flow of distribution networks, the safe operation of distribution networks can be guaranteed, thus greatly improving the utilization rate of new energy power generation.

Load state perception of distribution networks is to realize state monitoring and operation decisions of distributed power supply and equipment through processing and analyzing real-time measurement data. It aims at minimizing the reduction of renewable energy, and the problem of voltage violation in distribution networks is solved by reducing reactive power [25].

5.1. Dynamic Optimization of Reactive Power Compensation Equipment

Generally speaking, reactive power compensation technology is to switch capacitor in advance. It is characterized by a lack of judgment and initiative on the voltage limit.

The state-aware method proposed in this paper can realize active continuous control of reactive power compensation by tracking the node voltage in real time. The reactive power compensation device adopts constant voltage control mode, and all nodes are photovoltaic nodes. According to the node voltage, reactive power compensation is adjusted to realize the dynamic optimization of the node voltage of reactive power compensation equipment. When the output of the distributed power supply is much higher than the load demands, the line voltage level of the distribution network will rise. At this time, the reactive power compensation device absorbs reactive power, thus reducing the voltage level of the distribution network. When the output of the distributed power supply is far less than the load demands, the voltage level of the distribution network lines will decrease. The reactive power compensation device improves the voltage level of the distribution network by providing reactive power. If the reactive power output of this node reaches the limit, then PV nodes will become PQ nodes.

5.2. Dynamic Optimization of the Distributed Power Factor

The power factor of distributed generation is fixed, that is, the running state of the distribution network is not considered. The state-aware method proposed in this paper can dynamically adjust the power factor of a distributed power supply by tracking the node voltage in real time. The distributed power supply adopts the constant voltage control mode, and all nodes are PV nodes. According to the node voltage, reactive power compensation is adjusted to realize the dynamic optimization of the distributed power factor. When the voltage is too low, the power factor is adjusted to lag. At this time, the distributed power supply injects reactive power, thus increasing the voltage. When the voltage is too high, the power factor is adjusted to lead. At this time, the distributed power source absorbs reactive power, thus reducing the voltage. When the power factor adjustment limit is reached, PV nodes are converted into PQ nodes.

5.3. Optimal Reduction of Active Power Output of Distributed Power Supply

When the dynamic optimization of reactive power compensation equipment and the power factor of the distributed power supply cannot solve the problem of voltage overrun in the distribution network, it is necessary to further suppress the voltage overrun by optimizing the reduction of active output of the distributed power supply.

Firstly, the reduction rate index of the distributed generation is defined.

$$\delta_{\max} = P_{c,\max} / P_r \tag{26}$$

$$\delta = P_c / P_r \tag{27}$$

where $\delta_{\max}$ is the limit of the reduction rate; δ is the actual reduction rate; $P_{c,\max}$ is the limit of power reduction; P_r is the rated power; and P_c is the reduced power.

Secondly, with minimum power reduction as the goal, power balance, node voltage, branch power and the distributed power reduction rate are considered constraints. Its optimization model is:

$$\min \Delta P_{\mathrm{DG}c} = \sum_{l=1}^{N_{\mathrm{DG}}} \delta_l P_{r.l} \tag{28}$$

$$P_{\mathrm{s}} + \sum_{l=1}^{N_{\mathrm{DG}}} P_{\mathrm{DG}.l} = \sum_{i=1}^{N_{\mathrm{n}}} P_{\mathrm{load}.i} + \sum_{j=1}^{N_{\mathrm{b}}} \Delta P_{\mathrm{loss}.j} \tag{29}$$

$$Q_s + \sum_{l=1}^{N_{\mathrm{DG}}} Q_{\mathrm{DG},l} = \sum_{i=1}^{N_{\mathrm{n}}} Q_{\mathrm{load}.i} + \sum_{j=1}^{N_{\mathrm{b}}} \Delta P_{\mathrm{loss}.j} \tag{30}$$

$$V_{\min,i} \le V_i \le V_{\max,i} \tag{31}$$

$$S_j \leq S_{\max,j} \tag{32}$$

$$\delta_l \leq \delta_{\max,l} \tag{33}$$

where $\Delta P_{\mathrm{DG}c}$ is the total active power reduction; N_{DG} is the number of distributed power sources; δ_l is the reduction rate of the lth distributed power supply; $P_{r.l}$ is the rated output; P_{s} and Q_s are the active power and reactive power output of the substation, respectively; $P_{\mathrm{DG}.l}$ and $Q_{\mathrm{DG},l}$ are the active power and reactive power output, respectively; $P_{\mathrm{load}.i}$ and $Q_{\mathrm{load}.i}$ are the active load and reactive load, respectively; $\Delta P_{\mathrm{loss}.j}$ and $\Delta Q_{\mathrm{loss}.j}$ are the active and reactive power loss of branch j; S_j is the apparent power; δ_l is the reduction rate; and $\delta_{\max,l}$ is the maximum reduction rate.

6. Simulation Analysis

In this paper, wind turbine and photovoltaic generators are introduced according to the improved IEEE30-node, and the state-aware method is simulated. The structure of the system node is shown in Figure 1. The rated capacity of the fan is 1000 kW, the rated capacity of photovoltaic power generation is 800 kW, the initial working wind speed is 3 m/s, the extreme operating wind speed is 30 m/s, the photoelectric conversion rate is 20%, and the effective cross-sectional area of the photovoltaic panels is 3000 m^2. The main network is set as a balanced node and the load is set as a PQ node. The simulation platform is based on the seventh generation CPU of i7 and Matlab2021a on a computer with 16G memory, and it is solved by Gurobi solver. The loads of some nodes within 24 h are shown in Figure 2.

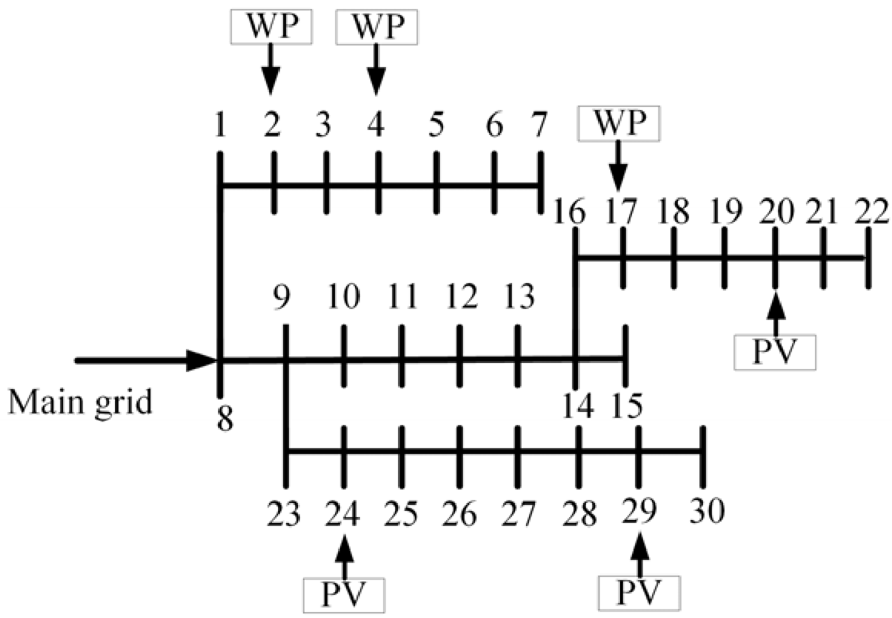

Figure 1. Improved IEEE 30 node distribution network system structure diagram.

First of all, the strong randomness of distributed power generation is considered. It is necessary to determine the access nodes of distributed generation according to the average connectivity index. Therefore, nodes 2, 4, and 17 and nodes 20, 24, and 29, with the strongest average connectivity index, are selected as wind power generation nodes and photovoltaic power generation nodes to ensure good connectivity of the distribution network under fault conditions. The performance indicators of these nodes are shown in Table 1.

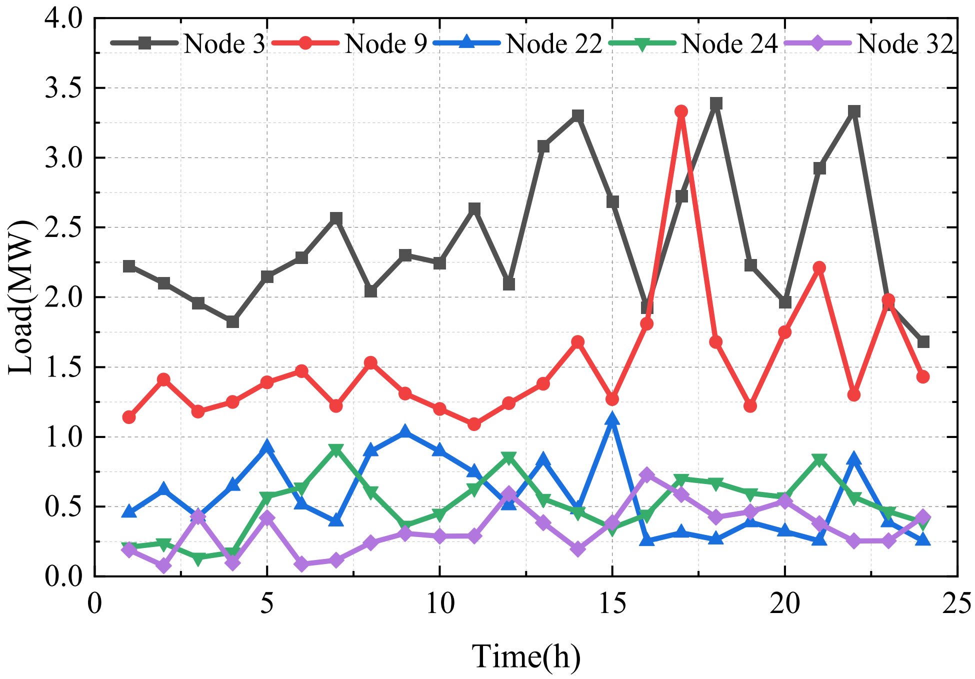

Figure 2. Daily load curve of some nodes.

Table 1. Typical risk indicators of typical nodes of the distribution network.

Node	Connectivity Index	Voltage Risk Indicators	Branch Load Risk Indicators	Risk Indicators of Branch Line Loss	Weighted Average Path
2	7.76	50.178	45.564	36.786	0.189
3	0.033	17.303	32.163	19.043	0.083
4	15.029	45.789	35.123	15.478	0.187
9	0.027	14.813	27.770	20.188	0.059
17	10.232	54.378	16.379	25.967	0.089
20	11.078	46.658	20.453	16.373	0.111
22	0.001	10.822	19.686	13.688	0.037
24	13.054	61.172	83.673	50.107	0.168
29	6.321	50.439	69.910	46.327	0.166
32	0.009	12.009	18.089	12.196	0.011

Secondly, the optimal weighted path is calculated according to the weighted network model. By establishing a node identification index system, the average path change index of the power grid under different operating conditions is obtained. Then, the average connectivity, the change indexes of node voltage, and branch load after the node fault state is relieved are calculated, in order to complete the construction of the node state awareness system. The change of the weight index of each node is shown in Table 1.

Then, based on the dynamic optimization strategy of load state perception operation risk, the index weight of typical nodes is obtained. The typical daily weight change diagram of the power grid is shown in Figure 3. As can be seen from the figure, the connectivity index has a high weight, generally floating around 0.4. Other indexes fluctuate around 0.2. Among them, the weight loss index of the branch line changes greatly, reaching 0.27 at 7 h.

Finally, according to the complex network theory and the node weight index, five key nodes in the distribution network system are selected to carry out simulation experiments with different distributed generation permeability. The changes of node voltage and branch load rate are analyzed when the permeability is 20%, 40%, 60%, and 80%, respectively.

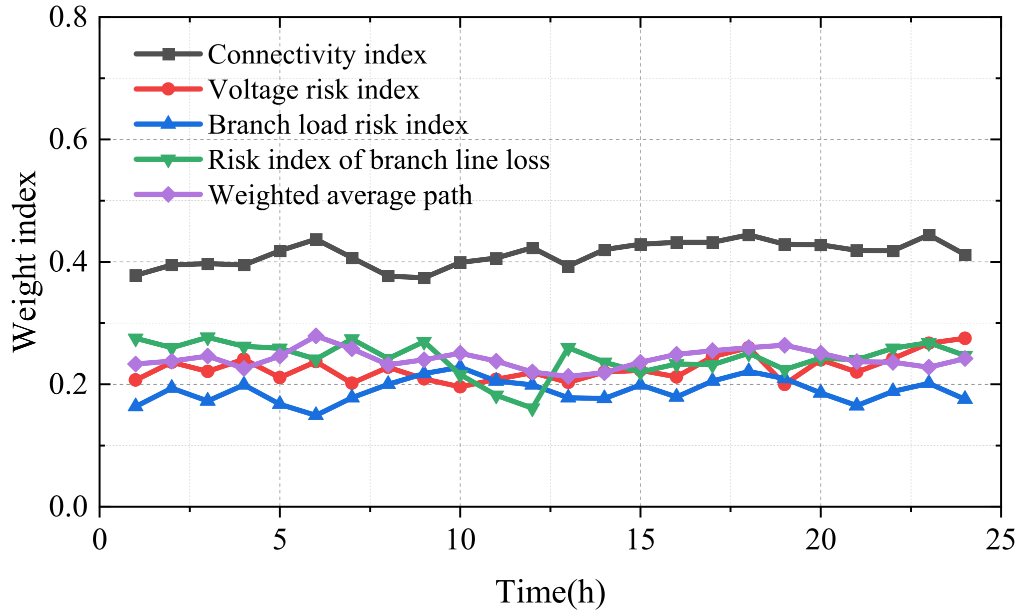

Figure 3. Typical daily weight index change.

In order to verify the risk of system voltage violation and the change of branch load rate under the distributed power supply access with different permeability, five scenarios are proposed, and they are compared and simulated. Scenario 1 sets the penetration rate of the distributed power supply at 80%. Scenario 2 sets the penetration rate of the distributed power supply at 60%. Scenario 3 sets the penetration rate of the distributed power supply at 40%. Scenario 4 sets the penetration rate of the distributed power supply at 20%. In Scenario 5, the distributed power supply cannot be obtained.

The unit value of node voltage under different distributed power supply permeability is shown in Figure 4. As can be seen from Figure 4, if the permeability of the distributed power supply is higher, the unit node voltage of each node is higher, and the risk of voltage overrun is higher. When the penetration rate of the distributed power supply is 80%, node 26 has reached the critical value of voltage overrun. According to Figure 5, it can be seen that after the distributed power is connected to the distribution network, with the increase of the proportion of distributed power access, the distribution network will have a certain degree of power reversal. This phenomenon easily leads to the increase of branch load rate. Therefore, the influence of distributed generation on the distribution network is gradually increasing with the increase of access rate.

As can be seen from Table 2, according to the method proposed in this paper, the node voltage deviation index is reduced by 13.00%, 3.75%, and 24.23%, respectively, when the distributed power penetration rate is 80%, 60%, 40%, 20%, and 32.83%. At this time, the overload index of branch load decreased by 6.03%, 6.25%, 16.89%, and 22.44%, respectively. According to the node voltage offset index and branch load overload index, the probability of voltage exceeding the limit caused by traditional access mode is directly proportional to the popularization rate of distributed generation. After the improved method is adopted in this paper, it can adjust the access mode in time, according to the early warning information, thus effectively reducing the probability of voltage exceeding the limit of the distribution network.

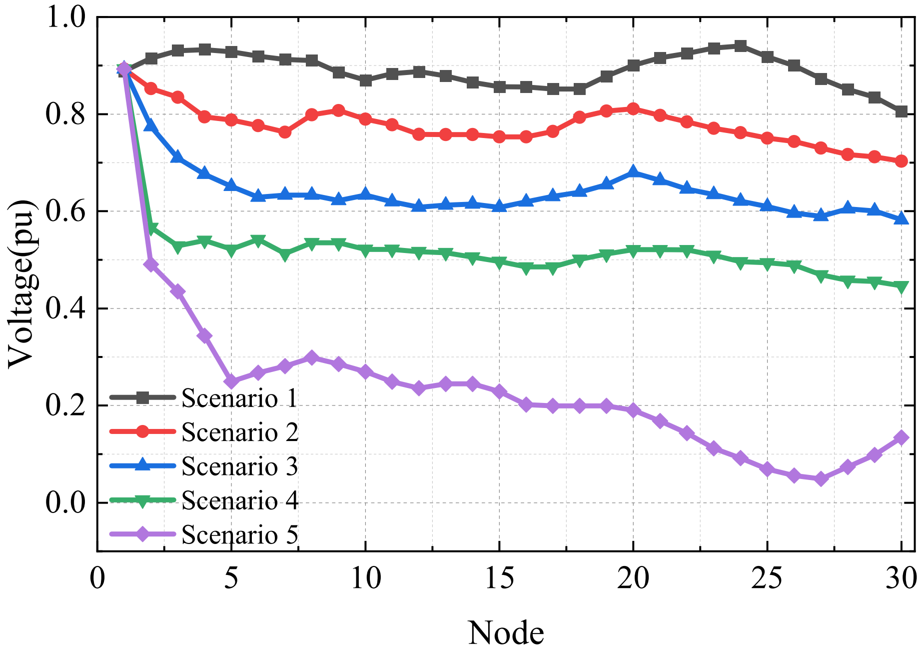

Figure 4. Unit value of node voltage under different distributed generation penetration rates.

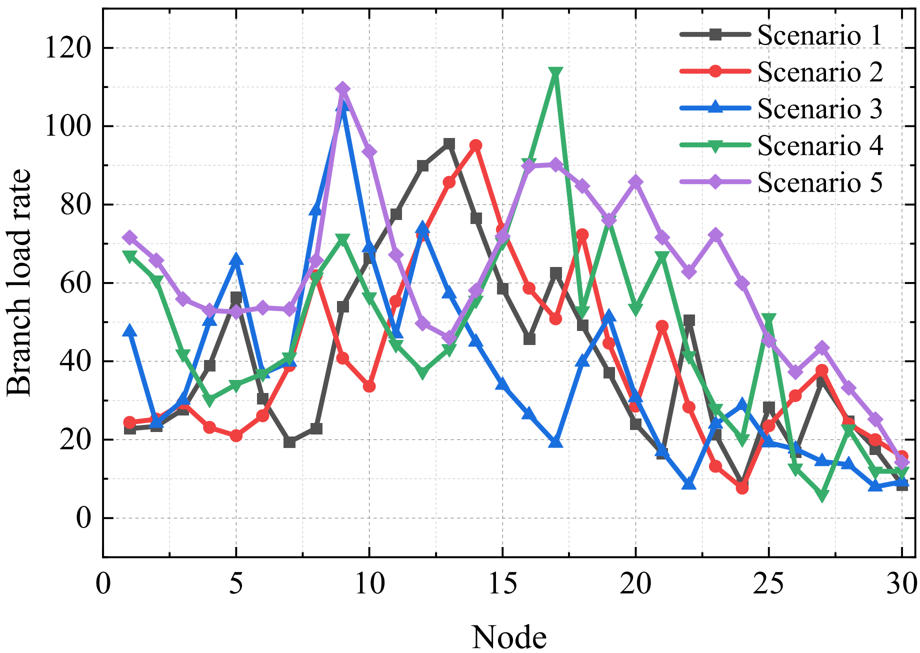

Figure 5. Branch load rate under different distributed power penetration.

Table 2. Comparison of the influence of different access methods on the distribution network.

Scenario	The method Proposed in the Ref. [18]		Proposed Method	
	Node Voltage Offset Index	**Branch Load Overload Index**	**Node Voltage Offset Index**	**Branch Load Overload Index**
Scenario 1	0.823	0.779	0.716	0.732
Scenario 2	0.587	0.432	0.565	0.405
Scenario 3	0.326	0.373	0.247	0.310
Scenario 4	0.198	0.156	0.133	0.121

7. Discussion

The distribution network is at the end of the power system and has a high degree of connection complexity and heterogeneity. Under the background of the current new power system, the penetration rate of the distributed power supply is gradually increasing, and the connection of a high proportion of power electronic devices will cause risks such as a voltage limit and load rate deviation, which pose huge challenges to the safe operation of the distribution network. Therefore, it is necessary to analyze the network connectivity index according to the structural characteristics of the distribution network grid, and select nodes with high stability as distributed power access nodes. At the same time, the risk index of voltage over-limit is calculated, the corresponding safety assessment is made, and the risk control strategy of distribution network operation is proposed. It provides a reference for distributed power access and operation.

The "distribution network load state perception method" proposed in this paper mainly uses the node voltage over-limit index and the branch load deviation index to identify the fault risk, thereby narrowing the fault detection range of the distribution network, sensing the state of the distribution network, and giving an early warning of the fault. Firstly, the distribution network is simplified and described as a set of nodes and a set of edges based on graph theory, and the dynamic characteristics of the distribution network are analyzed. Compared with the existing complex network model structure, describing the edge set and node set of the distribution network in the form of graph theory can more quickly and accurately mine the physical information relationship in the characteristic parameters of the distribution network. On this basis, the operation status and physical characteristics of the distribution network can be intuitively and accurately reflected by analyzing the weight of each side. Secondly, considering the probability density of node failure based on historical data, a risk index of node voltage violation is proposed to describe the severity of voltage excursion, the branch load deviation rate index is proposed to describe the severity of load overload, and the node connectivity index is proposed to describe the strength of the connection between the node and other nodes. Sampling analysis of power flow stochastic characteristics is based on the Monte Carlo method. The probability distribution model of the random process of distributed generation and load demand is established by using the non-parametric kernel density estimation method, and the power flow characteristics of the distribution network are analyzed under random conditions. Then, through the combination of optimal adjustment of reactive power compensation equipment, distributed power factor adjustment, and distributed power active output reduction technology, a dynamic optimization strategy for distribution network load state-aware operation risk is proposed, and the voltage over-limit problem of distribution networks is solved through reactive power compensation and active power reduction. Finally, through the improved IEEE30 node system, the node index weight is analyzed, and the distributed power access node is selected according to the connectivity index. In the five scenarios with different distributed power penetration rates, it can be seen that after the distributed generation is connected to the distribution network, as the proportion of distributed generation increases, the distribution network has a certain degree of power reverse, resulting in an increase in the load rate of the branch. Under the proposed access mode, the node voltage deviation index is reduced by 13.00%, 3.75%, 24.23%, and 32.83%, respectively, when the distributed power penetration rate is 80%, 60%, 40%, and 20%. The branch load deviation rate index is reduced by 6.03%, 6.25%, 16.89%, and 22.44%, respectively, when the distributed power penetration rate is 80%, 60%, 40%, and 20%. According to the node voltage offset index and the branch load overload index, with the increase of the penetration rate of the distributed power supply, the possibility of the risk of voltage exceeding the limit caused by the traditional access method is increasing. After adopting the method proposed in this paper, the distribution network adjusts the access mode in time, according to the early warning information, which effectively reduces the voltage limit risk of the distribution network. In practical applications, it can provide theoretical support for the access mode of distributed power generation and line maintenance.

8. Conclusions

In this paper, the power flow fluctuation caused by distributed power sources with different permeability connected to distribution networks is studied. At the same time, a load state perception model of distribution networks is proposed, and the access mode of distributed power supply is formulated according to the weight information.

(1) In this paper, the dynamic model of distribution networks based on complex network theory is established, and the operation risk index of distribution networks is put forward. The uncertainty caused by high penetration distributed generation access is analyzed, and the degree of expected risk is quantified.
(2) In this paper, the Monte Carlo method is used to sample and analyze the power flow of distribution networks, and a dynamic evaluation system of key nodes of distribution networks under different time scales is proposed. At the same time, this paper determines the access mode of high penetration distributed generation, and establishes the state awareness method system of distribution networks.
(3) In this paper, four access modes under different penetration rates of distributed power supply are proposed and simulated. Through the analysis of a node voltage deviation index and a branch load overload index, it is proven that this method can effectively improve the stability margin of distribution networks.

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Nomenclature

$C_t(L_{p_i p_j})$	electrical betweenness
P_i,P_j	corresponding node pair
S_{p_i}	weight of nodes v_i
S_{p_j}	weight of nodes v_j,
$I_{p_i p_j}$	current generated between the node pairs
P_t	node input power
D_{v_i}	average connectivity index
N	number of nodes
C_i	reciprocal of the sum of the electrical distances
W_{ij}	electrical distance
$\overline{D}_{v_i}$	strength of the stability of the distribution network structure
P_{vi}	out-of-limit probability index
N_{vi}	sampling times of out-of-limit behavior
N	total sampling times
$C_{\mathrm{Vvi},i}$	exceeding index
$P_{\mathrm{Vvi},i}$	exceeding probability
$\Delta V_{\mathrm{ave},i}$	average value of the exceeding index level
$\Delta V_{\mathrm{max},i}$	upper limit of the exceeding index limit level
$N_{\mathrm{Vvi},i}$	number of overruns drawn
$V_{i,k}$	node voltage value
$V_{\mathrm{lim},i}$	maximum value of voltage

$C_{\mathrm{Svi},j}$	out-of-limit indicator
$P_{\mathrm{Svi},j}$	probability of exceeding the limit of branch j
$\Delta S_{\mathrm{ave},j}$	average power over-limit level of branch j
$C_{\mathrm{Svi},s}$	out-of-limit indicator
N_{br}	number of branches
$N_{\mathrm{Svi},j}$	number of overruns
$S_{\max,j}$	rated capacity
v	speed
κ_{u}	upper limit of air clarity coefficient
$\overline{P}_{\mathrm{L}}$	average load value
σ	variance

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