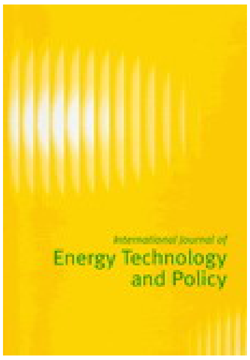

International Journal of Energy Technology and Policy

ISSN online: 1741-508X - ISSN print: 1472-8923
https://www.inderscience.com/ijetp

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DOI: 10.1504/IJETP.2025.10066469

Article History:

Received:	28 April 2024
Last revised:	04 June 2024
Accepted:	08 July 2024
Published online:	05 February 2025

Distributed generation planning method for active distribution network based on frog leaping algorithm

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Abstract: In order to improve the fault tolerance of the planned power grid and reduce the transmission loss rate, a frog leaping algorithm based distributed generation planning method for active distribution network is proposed. Considering the source load side fluctuation characteristics, a probability model is constructed to obtain the source load characteristics. Taking this as the input, probabilistic power flow calculation is carried out, and a bi-level programming model is constructed with opportunity constraints. Determine the upper power source location according to the probabilistic power flow calculation results. In order to improve the planning performance, the intermediate and acceleration factors are introduced to improve the frog leaping algorithm, so as to solve the lower level power configuration and realise the distributed generation planning of active distribution network. The results show that the proposed method has strong fault tolerance ability after planning, and the transmission loss rate is 5.8%. The longest planning time is 11.8 s.

Keywords: active distribution network; distributed generation planning; source load side fluctuation characteristics; leapfrog algorithm.

Reference to this paper should be made as follows: Deng, L., Wu, Q., Ao, Y. and Yu, Y. (2025) 'Distributed generation planning method for active distribution network based on frog leaping algorithm', *Int. J. Energy Technology and Policy*, Vol. 20, Nos. 1/2, pp.125–143.

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1 Introduction

With the continuous reduction of fossil fuel reserves, mankind is facing severe energy challenges. In this context, vigorously developing and utilising clean and renewable energy has become the consensus to solve the energy crisis. Renewable energy has the advantages of clean, environmental protection and recyclable regeneration. Vigorously developing and promoting renewable energy has far-reaching significance for realising the green transformation of the national economy, improving the ability of energy security, and building a resource-saving and environment-friendly society (Chen et al., 2023; Gangwar and Shaik, 2023). Therefore, distributed generation has been widely concerned and applied. In the development of electric power, energy transformation and upgrading is an important historical challenge. The development of traditional thermal power is restricted by fossil fuels and environmental protection, and the large-scale utilisation of distributed generation has become an important development direction of power energy transformation and upgrading (Qi, 2023). Distributed generation can not only effectively reduce energy consumption, but also improve the reliability of power supply, so as to meet the sustainable development needs of the power industry (Ouyang et al., 2022). With the continuous development and application of distributed generation technology, distributed generation has become an important part of the national energy reform. In the process of distribution network planning, the research of distributed generation planning is particularly important. By optimising the configuration of distributed generation, the operation efficiency and stability of power grid can be improved.

For this reason, relevant researchers have carried out research. For example, Vahid et al. (2021) proposed the optimal allocation and planning of power generation resources in an intelligent environment to reduce losses, and considered using manta ray foraging optimisation (MRFO) algorithm to enhance voltage distribution. However, in the application of distributed generation planning in active distribution network, the actual operation characteristics and constraints of distribution network are not fully considered, resulting in poor actual operation effect after planning. Lin et al. (2022) proposed a fixed capacity planning method for wind light storage access to distribution network. Considering the time sequence and other characteristics of distributed generation, the constraints are determined, and a multi-objective optimisation model is established, which is solved by the non-dominated sorting genetic algorithm to complete the distributed generation planning. Although the non-dominated sorting genetic algorithm can obtain the Pareto optimal solution set, the size and quality of the solution set are affected by the algorithm parameters and initial conditions, and the method does not fully consider this problem, which makes the planning effect fail to meet the expectation. Liu et al. (2023) combined with the operation characteristic model of generalised energy storage, built the operation planning model, and used the improved particle swarm optimisation algorithm to solve the planning scheme. However, this method does not fully consider the form of distributed generation and the source load side fluctuation characteristics, resulting in the inability to ensure the reliability of the planning in practical applications.

Therefore, based on the above research, in order to further optimise the configuration of distributed generation and improve the operation efficiency and stability of the power grid, the research on the distributed generation planning method of active distribution network based on frog leaping algorithm is proposed. The proposed algorithm can effectively realise the efficient utilisation of clean and renewable energy and promote the sustainable development of the power industry.

2 Probabilistic power flow calculation of distribution network considering source load side fluctuation characteristics

Distributed generation planning is an important content in the development and construction of smart grid and active distribution network, and it has randomness, volatility and uncertainty (Zhang et al., 2022; Divya and Arul, 2023), which makes it difficult to evaluate the operation status after access, resulting in poor effect of distributed generation planning. Therefore, considering multiple types of distributed generation forms and source load side fluctuation characteristics, the power flow calculation of distribution network is carried out to obtain the grid connected operation status of distributed generation and provide reliable support for subsequent distributed generation planning.

2.1 Probabilistic model construction considering source load side fluctuation characteristics

2.1.1 Probabilistic model of wind power generation

Wind power generation occupies an important position in the modern energy system because of its clean, environmental friendly and efficient characteristics (Huang et al., 2023). The wind speed is deeply affected by natural conditions, and its change often shows great uncertainty, which makes it difficult to predict. Therefore, in order to describe the variation characteristics of wind speed more accurately, Weibull distribution is used to describe it, so as to understand and analyse the fluctuation law of wind speed more scientifically, so as to provide strong support for the prediction, scheduling and optimisation of wind power generation. The specific formula is as follows:

$$f_w(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \tag{1}$$

where v is the actual wind speed, and c, k is the scale and shape parameter of Weibull distribution. The calculation formulas of c and k are as follows:

$$\begin{cases} k = \left(\dfrac{\sigma}{\mu}\right)^{-1.086} \\ c = \dfrac{\mu}{\Gamma(1+1/\ k)} \end{cases} \tag{2}$$

where, Γ is the gamma function, μ is the mean value, and σ is the standard deviation.

2.1.2 Probability model of photovoltaic power generation

Light intensity is the key factor to determine the output of photovoltaic power generation unit (Dong et al., 2022), but it is affected by many factors, such as altitude, climate conditions, seasonal changes and so on, with great randomness. Therefore, in order to better understand and predict the change law of light intensity, the beta distribution can be used to construct the probability model of light intensity, so as to more accurately describe the distribution characteristics of light intensity, and provide a more scientific basis for the site selection of photovoltaic power plants. Then the constructed probability model of light intensity is as follows:

$$f(r) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{r}{r_{\max}}\right)^{\alpha-1}\left(1-\frac{r}{r_{\max}}\right)^{\beta-1} \tag{3}$$

where α and β are dimension and shape parameters, r. $r_{\max}$ is the radiation intensity and its maximum value.

Shape parameter α of beta distribution α, β. The specific formula is as follows:

$$\begin{cases} \alpha = \mu\left[\dfrac{\mu(1-\mu)}{\sigma^2}-1\right] \\ \beta = (1-\mu)\left[\dfrac{\mu(1-\mu)}{\sigma^2}-1\right] \end{cases} \tag{4}$$

Therefore, based on the probability model of light intensity, the probability density function of distributed photovoltaic power generation can be obtained to describe the variation characteristics of photovoltaic, which has the following formula:

$$f(P_{solar}) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{P_{solar}}{P_{solarm}}\right)^{\alpha-1}\left(1-\frac{P_{solar}}{P_{solarm}}\right)^{\beta-1} \tag{5}$$

where P_{solar} and P_{solarm} are the output power and its maximum value respectively, $P_{solarm} = r_{max}A\eta$, A is the effective radiation area, and η is photoelectric energy conversion efficiency.

2.1.3 Load probability model

The power generation and consumption of the power system are balanced in real time, and the power consumption depends on the user's power consumption habits and power consumption plan, which is random (Copp et al, 2022; Moya et al., 2022). In order to ensure that the power flow calculation results truly reflect the system operation status, full consideration should be given to the random change of load (Li et al., 2022). Therefore, after obtaining the above change characteristics, the normal distribution is used to represent the load probability model to describe the change characteristics of the load, as follows:

$$\begin{cases} f(P_L) = \dfrac{1}{\sqrt{2\pi}\sigma_{PL}} \exp\left[-\dfrac{(P_L - \mu_{PL})}{2\sigma_{PL}^2} \right] \\ f(Q_L) = \dfrac{1}{\sqrt{2\pi}\sigma_{QL}} \exp\left[-\dfrac{(Q_L - \mu_{QL})}{2\sigma_{PL}^2} \right] \end{cases} \tag{6}$$

where σ_{PL} and σ_{QL} are the standard deviation of the probability distribution of active and reactive loads respectively, and μ_{PL}, μ_{QL} is the mean value of probability distribution of active and reactive load respectively.

2.2 Probabilistic power flow calculation

In order to analyse the impact of various randomness on power grid operation and master the real operation status of power grid, the concept of probabilistic load flow (PLF) was born. It can fully consider various uncertain factors, mine the operation characteristics of power system, and provide data support for power grid operation control, stability analysis and state assessment (Sun et al., 2022; Jiang et al., 2022). Therefore, the Monte Carlo simulation (MCS) method is selected to complete the power flow calculation of distributed generation distribution network (Singh and Byun, 2023; Wang and Chan, 2023), which does not need to know the functional relationship between the input and output in advance. A large number of sample data are generated through the simulation sampling of the input probability model, which is brought into the system model to determine the required data. Finally, the characteristic values are obtained through mathematical statistical calculation to reflect the operation characteristics. Therefore, in power flow calculation, the variation characteristics obtained from the above wind and light distributed generation and load probability models are used as inputs. The specific steps are as follows:

1 According to Section 2.1, the probability characteristic values obtained from a large number of collected wind speed, light intensity and load data are calculated to obtain the probability distribution functions of wind power generation, photovoltaic power generation and load fluctuation.

2 According to the probability distribution function of the system random input variables, Monte Carlo simulation sampling is used to generate a large number of sample banks.

3 All sample data are brought into the distribution network power flow calculation model to obtain the hourly data of the distribution network. The system power flow calculation results are obtained by applying the forward and backward substitution method, and the probability characteristics of the system output variables (voltage, network loss, etc.) are obtained, which are specifically expressed as follows:

a Initialisation: initialise the initial value data of distribution network voltage of each node obtained by power flow calculation, which is usually set as rated voltage.

b Start from the end node: for each node, calculate the current flowing into the node according to the voltage and branch impedance of the downstream node, as follows:

$$I_{ij} = \frac{S_{ij}}{V_i} \tag{7}$$

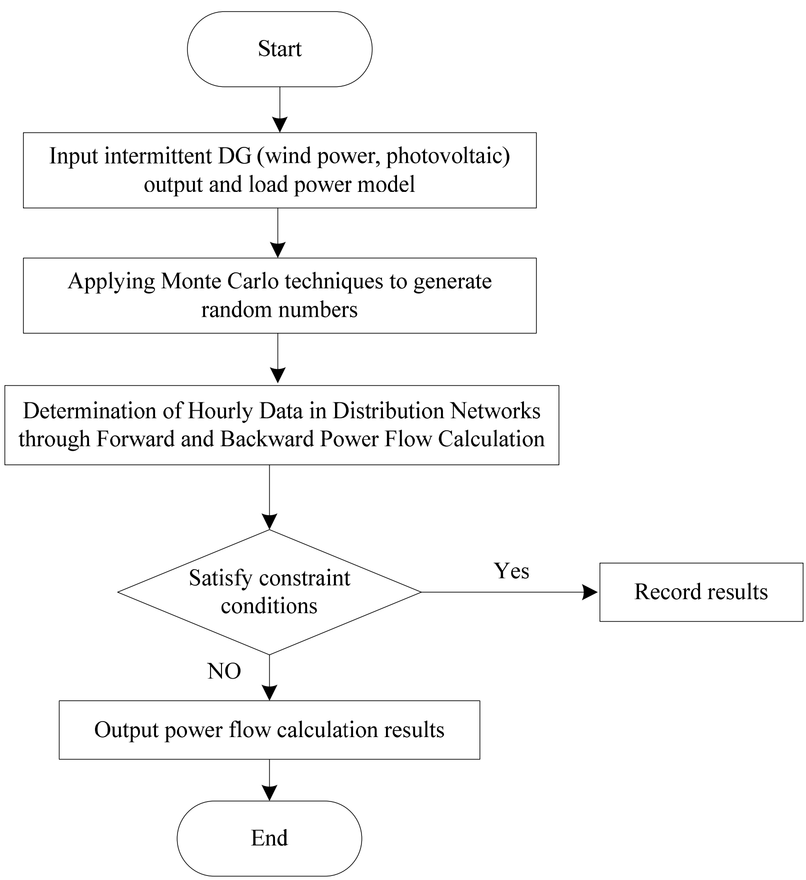
where I_{ij} is current, S_{ij} is complex power conjugate, and V_i is voltage conjugate.

c Push towards the upstream node: use Kirchhoff current law to calculate the injection current of each node, as follows:

$$\sum I_i = \sum\nolimits_{j \in downstream\ of\ i} I_{ij} - \sum\nolimits_{k \in upstream\ of\ i} I_{ki} \tag{8}$$

where $\sum I_i$ is the total injection current of the node.

Figure 1 Monte Carlo probabilistic power flow calculation process



According to this, the node voltage is updated, and the forward and backward processes are repeated until the voltage and current of all nodes converge to meet the accuracy requirements. Node voltage updates are as follows:

$$V_i^{new} = \frac{\left(f_w(v) + f\left(P_{solar}\right)\right)V_i^{old} - Z_i \sum I_i}{f\left(P_L + f\left(Q_L\right)\right)} \tag{9}$$

where V_i^{new} and V_i^{old} are the old and new voltage values of node i respectively, and Z_i is the self impedance of node i.

The specific implementation process is shown in Figure 1.

3 Implementation of distributed generation planning in active distribution network based on frog leaping algorithm

The core content of distributed generation planning in distribution network is the selection of installation nodes and the optimisation of configuration capacity. In order to achieve effective distributed generation planning in active distribution network, a bi level planning model of distributed generation is established based on the above content. However, in the power grid planning, many uncertain factors should be taken into account to ensure the safe and reliable operation in case of emergencies. Because the design scheme after meeting all the constraints cannot be implemented or is not feasible at all. Therefore, the purpose of using chance constrained programming (CCP) for constraint is to solve the programming problem with random variables, and the core is to allow the occurrence of small probability events that do not meet the constraint conditions. On this basis, in order to complete the distributed generation planning of active distribution network, frog leaping algorithm is used to solve the model under constraints. In order to avoid falling into local optimal solution, intermediate factor and acceleration factor are introduced to improve the frog leaping algorithm to ensure the reliability of the solution, so as to achieve accurate and reasonable distributed generation planning of active distribution network.

3.1 Construction of chance constrained programming model

The distributed generation planning problem of distribution network considering the source load side fluctuation characteristics includes many random variables such as wind power output, photovoltaic output and load fluctuation, which need to meet a series of equality and inequality constraints of system operation. The deterministic planning method is difficult to meet all constraints. Therefore, CCP is used to express some constraints in the distributed generation planning problem, and a certain confidence level is set for the constraints containing random variables, which requires that the constraints occur within the range of probability. When establishing the chance constrained programming model, based on the system operation state data obtained from power flow calculation, the deterministic constraints are transformed into opportunity constraints by setting the confidence level. The mathematical expression of CCP is as follows:

$$\begin{cases} \min f\left[f_1, f_2, ..., f_n\right] \\ s.t. \\ \Pr\left\{G_i(x, \delta) \le 0\right\} \ge \alpha_i \\ U(X) = \le 0 \\ B(X) = 0 \end{cases} \tag{10}$$

where $f_i(i = 1, 2, ..., n)$ represents the objective function, which can be multiple according to different planning problems. $U(X)$ is the set of inequality constraints in the programming problem. $G_i(x, \delta)$ is the opportunity constraint in the planning problem. $B(X)$ is the set of equality constraints in the programming problem. α_i is the confidence level. δ is a random variable. $\Pr\{\cdot\}$ is the probability of occurrence. x is the optimal control variable.

3.2 Bi-level multi-objective programming model

Then, the constraints are determined by combining the chance constrained programming theory, and the state variable constraints are transformed into chance constraints in the constraints. A bi-level programming model with the upper layer as site selection and the lower layer as capacity configuration is constructed. The active power loss sensitivity index is used to determine the installation location of distributed generation, and the investment income, network loss and voltage stability are considered to determine the configuration.

3.2.1 Upper layer location model

In the past, when locating the distributed generation, it was generally installed around the power demand centre, which played a role in reducing the network transmission loss and supporting the local voltage level. However, for a certain distribution network system (without considering the change of grid structure), the load change of a single node has a great impact on the system network loss, and the impact of load change of different nodes on the system network loss is different. After the distributed generation is connected as PQ node, the node equivalent load will be changed. From the perspective of reducing network transmission loss, reasonably selecting the installation location of distributed generation can better play a positive role in energy saving and loss reduction in the grid connected operation of distributed generation. Therefore, the sensitivity of active power loss is taken as the objective function of DG location, as follows:

$$T_i = \left| \left(P_i^2 + Q_i^2\right) \sum R_{si}^2 + 2P_i \sum R_{si} \left(P_i \sum R_{si} + W_i \sum X_{si}\right) - \left(P_i \sum R_{si} + W_i \sum X_{si}\right)^2 \right| \tag{11}$$

where T_i is the sensitivity value of active network loss. P_i and Q_i is active load and reactive load respectively. R_{si} and X_{si} is the equivalent resistance and reactance between node s and node i respectively. When the distributed generation is installed on the node with larger T_i, the effect of local load accommodation on the reduction of system network loss is more significant. On the contrary, the effect of installing distributed generation on this node is not obvious. By calculating the T_i value of all nodes in the network and sorting them, the optimal access node is reasonably selected according to the sorting results and the actual operation status of the distribution network obtained from the above power flow calculation, so as to determine the installation location of distributed generation.

3.2.2 Lower level configuration model

After the upper layer location model obtains the installation location, taking into account the investor's income, power grid operation reliability and safety, the optimal configuration model is established with the multi-objective of distributed generation investment income, network transmission loss and system voltage quality.

3.2.2.1 Investment income evaluation index

From the economic perspective of the investment in the construction of distributed generation, the annual investment expenditure and expected return are applied to build the investment income

The evaluation index is:

$$C_{PSC} = \frac{C_{TPF}}{C_{INV}} \tag{12}$$

where C_{TPF} is the annual profit, and C_{INV} is the annual investment cost. Then the annual income and investment cost model is:

$$C_{TPF} = 8760\sum_{i=1}^{N_{DG}} \left(C_{Si} + C_{Bi}\right) S_{DG_i} \lambda_i \tag{13}$$

$$C_{INV} = \sum_{i=1}^{N_{DG}} \chi_{DGi} S_{DGi} C_{Ti} + 8760\sum_{i=1}^{N_{DG}} C_{Fi} S_{DGi} \lambda_i \tag{14}$$

where λ_i is the capacity coefficient of type i power supply. χ_{DGi} is the annual investment cost conversion coefficient of type i power supply. C_{Fi} is the operation and maintenance cost of type i power supply. C_{Ti} is the unit installation capacity investment cost of i-type power supply (equipment procurement cost and installation cost). S_{DGi} is the access capacity of type i power supply. NDG is the number of power supply types involved in the planning. C_{Si} and C_{Bi} is the electricity price of i-type power supply and state support subsidies.

3.2.2.2 Network loss evaluation index

From the perspective of power grid operation economy, after the distributed generation is installed in the distribution system, it can not only optimise the power flow distribution of the system, make the current flow in the power grid more reasonable and efficient, but also effectively reduce the network loss, reduce unnecessary energy loss, and improve the system operation economy. The system network loss evaluation index is established as follows:

$$P_{loss} = \sum_{i=1}^{N}\sum_{j=1}^{M}\left[V_i^2 Y_{ij}\cos\theta_{ij} - V_i V_j Y_{ij}\cos\left(\delta_{ij} + \theta_{ij}\right)\right] \tag{15}$$

where N and M are the total number of distribution system nodes and load nodes respectively. V_i is the voltage amplitude of node *i*. Y_{ij}, θ_{ij} is admittance parameter and impedance angle respectively. δ_{ij} is the voltage phase angle difference.

3.2.2.3 Voltage evaluation index

From the perspective of grid voltage reliability, the grid connected operation of distributed generation can effectively improve the system voltage level and system operation reliability. Using voltage deviation index v_1 and branch voltage index v_2, the voltage evaluation index is constructed as follows:

$$v_1 = \sum_{i=1}^{N} \left| V_i - V_{rate} \right| \tag{16}$$

$$v_2 = \sum_{i=1}^{N} \sum_{j=1}^{M} \frac{4\left[\left(P_j X_{ij} - Q_j R_{ij} \right)^2 + \left(P_j R_{ij} + Q_j X_{ij} \right) v_i^2 \right]}{v_i^4} \tag{17}$$

where V_{rate} is the system reference voltage and R_{ij} is the impedance of branch *ij*. Voltage deviation index v_1 refers to the sum of the absolute values of all node voltages and reference voltages of the system. It describes the deviation degree of system voltage. The smaller v_1 and v_2 are, the higher and more stable the voltage level is. Combined with the above two voltage indexes, a comprehensive voltage stability evaluation index is established to comprehensively evaluate the voltage condition after the connection of distributed generation. The voltage stability index is as follows:

$$U = \alpha_1 v_1 + \alpha_2 v_2 \tag{18}$$

where α_1 and α_2 are weight coefficients.

According to the chance constrained programming model constructed in 3.1, the configuration layer operation constraints can be divided into conventional equality constraints, inequality constraints and chance constraints, as follows:

$$\begin{cases} P_i - P_{DG\_i} = V \sum_{j=1}^{N} V_j \left(G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij} \right) \\ Q_i = Q_{DG\_i} = V_i \sum_{j=1}^{N} V_j \left(G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij} \right) \\ P_r \left\{ V_i^{\min} \le V_i \le V_i^{\max} \right\} > \beta \\ P_r \left\{ S_{ij} \le S_{ij}^{\max} \right\} > \delta \\ \sum_{i=1}^{N_{DG}} P_{DG\_i} \le \delta \sum_{i=1}^{N} P_i \\ S_{DG\_i} \le S_{DG\_i}^{\max} \end{cases} \tag{18}$$

where P_{DG_i} and Q_{DG_i} are active and reactive output power respectively. P_i and Q_i active and reactive load demand. G_{ij} and B_{ij} is admittance and susceptance respectively. $V_i^{\min}$ and $V_i^{\max}$ is the minimum and maximum voltage amplitude respectively. χ is the permeability capacity coefficient of distributed generation in distribution network. S_{ij} is the transmission power. $S_{ij}^{\max}$ is the maximum conveying capacity. S_{DG_i} and $S_{DG\_i}^{\max}$ is the installed capacity and maximum allowable installed capacity of the distributed power supply at the node. β and δ is the confidence level of the set opportunity constraint condition (usually expressed in the form of probability), which is set to 0.9. $P_r\{\cdot\}$ is the probability that the opportunity constraint condition holds.

3.3 Solution of lower level configuration model based on frog leaping algorithm

Shuffled frog leaping algorithm (SFLA) can efficiently explore the solution space of the problem, and then find the optimal solution of the problem. The algorithm can maintain a certain local search ability in the search process, thus effectively balancing the relationship between exploration and utilisation (Yi et al., 2023; Liu et al., 2022). Due to the simplification of communication mode in the search process of SFLA (frog leaping algorithm), the search space is reduced, which makes it easy to fall into local optimal solution and converge prematurely in solving multi-objective programming problems. Therefore, the intermediate factor and acceleration factor are introduced to improve the frog leaping algorithm. By introducing an intermediate factor, the algorithm can maintain the diversity of the population and guide the algorithm to search in the direction where it is more likely to find the global optimal solution. The introduction of acceleration factor can accelerate the convergence speed and avoid falling into local optimal solution. These improvements not only enhance the robustness of the frog leaping algorithm but also improve its efficiency and accuracy in solving multi-objective planning problems. These ensure the reliability of the lower-level configuration model in active distribution network distributed generation planning, achieve accurate and reasonable active distribution network distributed generation planning, and effectively improve the operation efficiency and stability of the power grid.

3.3.1 Improvement of frog leaping algorithm

3.3.1.1 Introduction of intermediate factor

Based on the idea of binary search method, the following improvements are proposed: after sorting the frog group, the worst performing frog is excluded, and then the fitness average of the remaining individuals is calculated as the intermediate factor X_a. Next, the whole frog population was remixed and divided into two sub populations according to certain rules, and the average values were calculated, which were X_{ave1} and X_{ave2}. Then, the average fitness value of each population was compared with the intermediate factor. If the average fitness value of a population is lower than the fitness value corresponding to the intermediate factor, the population is considered to have poor performance and will be eliminated. After the culling operation, select the reserved population to update the frog that was identified as the worst before. After the update operation is completed, the search is not stopped, but the above operations are repeated within the population that has not been eliminated, that is, recalculate the average value, compare, eliminate and update. In this way, the structure of frog swarm can be continuously optimised to make it closer to the optimal solution of the problem. The specific location update strategy is shown in equations (19)–(21).

$$X_a = \frac{1}{n}\sum\nolimits_{i=2}^{n} X_i \tag{19}$$

$$St = C \cdot rand() \times (X_b - X_{ave}) \tag{20}$$

$$X_{new} = X_w + St\left(St_{\min} \le St \le St_{\max}\right) \tag{21}$$

where X_i represents other individuals except for the worst fitness individual X_w, C is acceleration factor, St is the step allowed to be changed by the worst child, X_b is the individual with the minimum fitness, *rand*() is a random function, and $St_{\min}$ and $St_{\max}$ are the lower and upper limits of the step size.

In the frog leaping algorithm, the position of the worst frog is adjusted by introducing the intermediate factor X_a, which not only promotes the evolution process of the whole frog population, but also ensures that the algorithm will not ignore the information of other potential excellent individuals in the search process and avoid premature convergence to the local optimal solution. When the system is suddenly disturbed by external interference, because the frog leaping algorithm has a large number of frogs and each individual actively participates in the search process, the algorithm can quickly respond and adjust the search strategy, so as to effectively improve the stability of the system. This strong robustness makes the frog leaping algorithm have significant advantages in solving complex optimisation problems.

3.3.1.2 Introduction of acceleration factor

If the step size is too small, the moving pace of the algorithm in the search space will become cautious and slow, which will undoubtedly weaken its ability of global search, resulting in low efficiency of the algorithm in finding the optimal solution. But the step size is too large, which leads to too aggressive in the search process, skipping the real optimal solution, and falling into the dilemma of local optimisation, so that the global optimal solution of the problem can not be obtained.

In SFLA algorithm, its step size can not adapt to the complexity and diversity of all problems. Therefore, an acceleration factor greater than 1 is introduced to increase the step size so that it can converge to the local optimal solution faster.

3.3.2 Multi objective solution of improved SFLA

Under the constraint of formula (18), each index in the lower level configuration model is taken as the fitness function, and the SFLA algorithm improved by the above strategy is used to carry out multi-objective solution to obtain the optimal configuration of distributed generation in active distribution network. Combined with the site selection results obtained in 3.2.1, the distributed generation planning of active distribution network is realised. The specific process is described as follows.

M frog individual (which is the configuration of distributed generation in active distribution network) is randomly generated to form the initial species group $P = \{X_1, X_2, ..., X_M\}$. These frog individuals represent different distributed generation configuration schemes in the solution space. In order to evaluate the advantages and disadvantages of these configuration schemes, the individual fitness values are calculated and arranged in descending order, and the individual X_{glo} with the lowest fitness is recorded, which represents the worst configuration scheme in the current population. Next, these individual frogs will be allocated to sub population *m* according to specific rules. When the upper limit of individual number of sub population is reached, the next frog will be re allocated from sub population 1 to ensure the balance of individual number in each sub population.

In order to ensure the best configuration scheme, the position is updated according to the previously mentioned formulas (20)–(21). If the performance of the updated frog is better, the original individual will be replaced. If the performance is not improved, the update strategy will be used again to adjust the position of the worst frog. If the fitness value is still not improved after many attempts, the frog individuals in the population will be randomly selected to replace the original worst frog. Repeat the above process until the maximum number of convergence is reached, and then the update iteration is ended. Finally, the best distributed generation configuration scheme of active distribution network will be output.

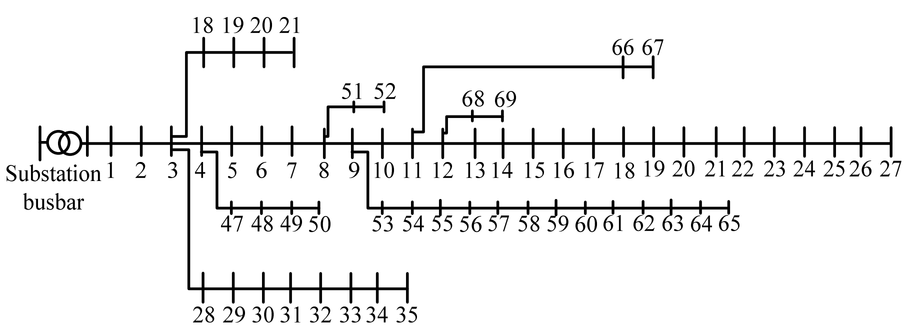
To sum up, the optimal configuration of distributed generation in active distribution network is obtained, and the distributed generation planning is completed in combination with the installation location of distributed generation reasonably determined in 3.2.1 above.

4 Experimental test

4.1 Examples and parameters

In order to verify the rationality of the configuration model proposed in this paper, IEEE-69 node distribution system is used as a test example, and the structure is shown in Figure 2.

Figure 2 Topological structure of distribution system



Matlab software is used for programming and calculation. The probability distribution parameters related to the probability models of wind power, photovoltaic and load are shown in Table 1.

Table 1 Parameters of wind, light power and load probability model

Photovoltaic power generation				Power load			
k	c	η	A	σ_P	σ_Q	μ_P	$\mu\sigma_Q$
5	1.8	13.44%	1,000 m^2	0.2	0.2	9MW	9MW
Wind power generation							
k	c	v_{ci}	v_{co}	v_r			
6.5	2.0	3	20	15			

The confidence levels β and δ are set to 0.9, the upper limit of grid distributed generation penetration is 40%, and the allowable range of node voltage fluctuation is [–5%, +5%].

4.2 Test indicators

On the basis of the above settings, the effect evaluation indicators of the distributed generation planning method for active distribution network are determined as follows:

1 Power grid fault tolerance refers to that the power grid should be able to maintain a reasonable voltage and frequency level in case of fault, so as to ensure the normal operation of power equipment and the power quality of users. Therefore, the stability of voltage and frequency can be used to measure the fault tolerance of power grid.

2 Energy efficiency refers to the economic benefits of the overall grid operation cycle after considering the planned access of distributed generation, which can be measured by calculating the transmission loss rate of the grid. The low transmission loss rate shows that the planning method can effectively improve the economic benefits and energy efficiency of the power grid. The transmission loss rate of the grid is calculated as follows:

$$\text{Transmission loss rate} = \left(\text{Energy lost from transmission lines} / \text{Total energy transmitted}\right) \times 100\%$$

3 The time complexity index can evaluate the efficiency of distributed generation planning and ensure its feasibility in practical application. The test is completed in MATLAB. In order to record the duration of distributed generation planning method, tic TOC function is selected to record the code running duration of the method. The code running time is equal to the planning time of the method. The shorter the time, the higher the efficiency of the proposed method in distributed generation planning.

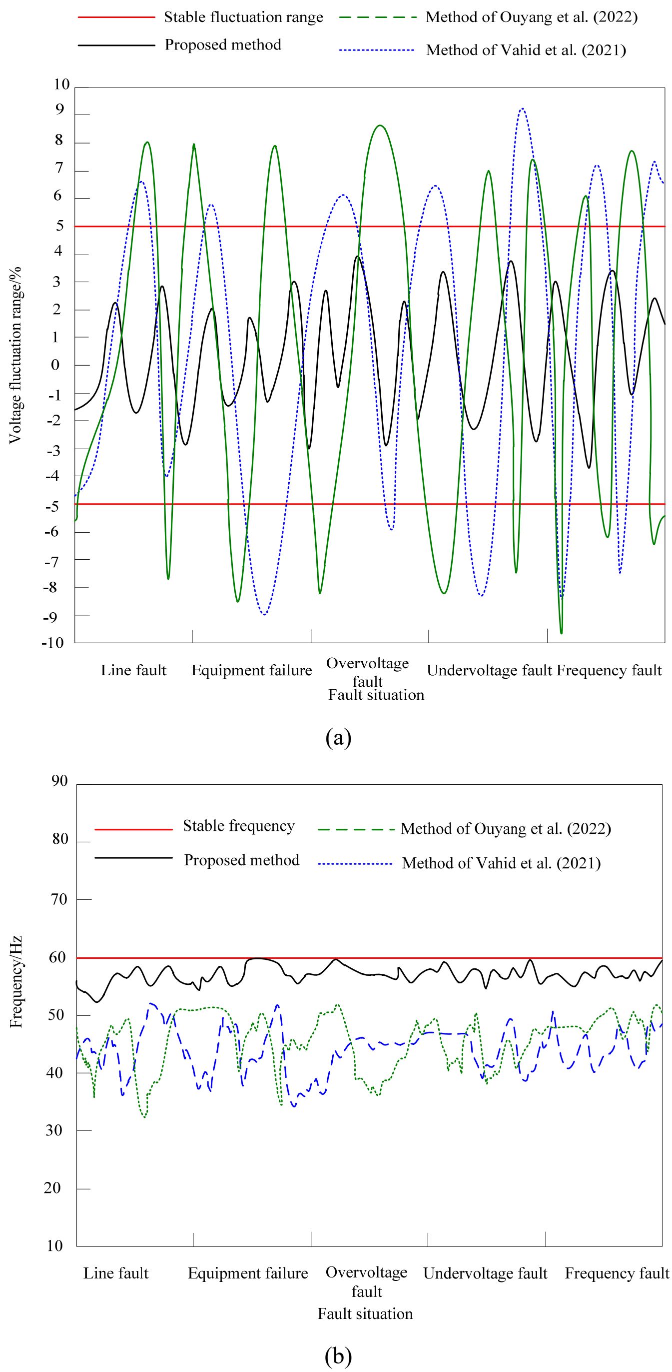
Therefore, considering the above multiple test and evaluation indexes, the Vahid et al. (2022) method and Lin et al. (2022) method are used as the comparison methods to carry out the comparison test with the proposed method to complete the performance verification

4.3 Result analysis

4.3.1 Result analysis of power grid fault tolerance

For the grid fault tolerance index, the proposed method, Vahid et al. (2022) method and Lin et al. (2022) method are respectively used for active distribution network distributed generation planning, and the grid fault tolerance of the planning results are tested. The voltage and frequency results of the three methods in the case of line fault, equipment fault, overvoltage fault, undervoltage fault and frequency fault are shown in Figure 3.

Figure 3 Voltage and frequency results of three methods, (a) voltage results (b) frequency results (see online version for colours)



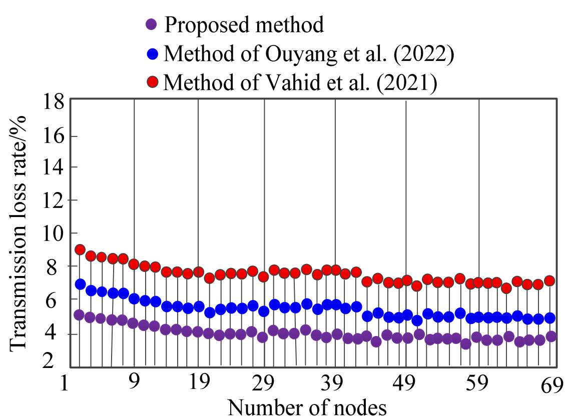
According to the results obtained in Figure 3, using the proposed method for distributed generation planning of active distribution network, the power grid can maintain reasonable voltage and frequency levels under five types of faults, which can effectively ensure the normal operation of power equipment and the power quality of users. However, using the Vahid et al. (2021) method and Lin et al. (2022) method for distributed generation planning of active distribution network, the power grid can not be maintained at a reasonable voltage and frequency level under five types of faults. This shows that the proposed method has more power grid fault tolerance and more reliable planning results than the Vahid et al. (2021) method and Lin et al. (2022) method.

4.3.2 Analysis of energy efficiency results

In order to verify the economic benefits of the proposed method, the proposed method, Vahid et al. (2021) method and Lin et al. (2022) method are used for active distribution network distributed generation planning for energy efficiency indicators, and the transmission loss rate of the planning results is tested. The transmission loss rate results of the three methods are shown in Figure 4.

According to the results obtained in Figure 4, the transmission loss rate of the above three methods for active distribution network distributed generation planning is less than 10%, but compared with the transmission loss rate results of the three methods, the proposed method has a low transmission loss rate of 5.8%. While using the Vahid et al. (2021) method and Lin et al. (2022) method for active distribution network distributed generation planning, the highest transmission loss rates are 7.7% and 8.7%, respectively. This shows that the proposed method has a lower transmission loss rate and can effectively improve the economic benefits and energy efficiency of the power grid.

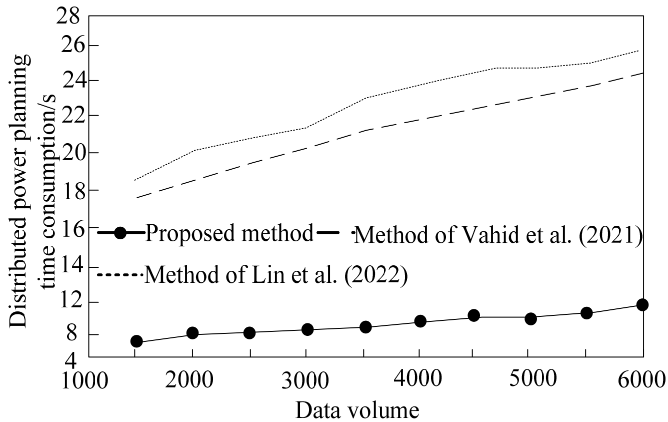
Figure 4 Transmission loss rate results of three methods (see online version for colours)



4.3.3 Time complexity result analysis

On the basis of the above tests, the proposed method, Vahid et al. (2021) method and Lin et al. (2022) method are tested for the time complexity index. In MATLAB, the tic TOC function is used to record the planning time of the method, and the results are shown in Figure 5.

Figure 5 Distributed generation planning time



According to Figure 5, the planning time of the three distributed generation planning methods increases with the increase of the number of samples. When the number to be planned reaches 6,000, the planning time of the proposed method is 11.8 s, while that of the Vahid et al. (2021) method and Lin et al. (2022) method is 24 s and 25.7 s, respectively. By comparing the three methods, it can be concluded that the proposed method takes less time for distributed generation planning, which shows that the proposed method has lower time complexity, faster distributed generation planning speed, more feasibility, and can play a greater value in practical application.

5 Conclusions

In today's power system, the rational planning of distributed generation is of great significance for improving the operation efficiency of power grid, ensuring the quality of power supply and realising the sustainable development of energy. With the continuous development and improvement of active distribution network technology, the planning of distributed generation has been paid more and more attention. The frog leaping algorithm based distributed generation planning method for active distribution network proposed in this paper aims to optimise the planning effect of distributed generation, improve the fault tolerance of the planned power grid, and reduce the transmission loss rate. Firstly, a probabilistic model is constructed considering the source load side fluctuation characteristics to obtain the source load variation characteristics. Secondly, taking this as the input, Monte Carlo simulation method is used for probabilistic power flow calculation to obtain the characteristic numerical response operation characteristics. Then, many random variables are fully considered, and the conditional constraints are determined by combining the chance constrained programming theory, and a bi-level programming model is constructed. Finally, according to the results of probabilistic power flow calculation and the sensitivity of active power loss, the position of distributed generation in the upper layer is determined. The improved frog leaping algorithm is used to solve the lower level distributed generation configuration and complete the distributed generation planning of active distribution network. The results show that the proposed method has strong fault tolerance ability, and the maximum transmission loss rate is 5.8%. The maximum planning time is 11.8 s, with strong planning performance, which can effectively improve the efficient utilisation of clean and renewable energy and promote the sustainable development of the power industry.

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