The distribution network planning considering distributed power supply and battery energy storage base on IMO-SLFA

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Abstract. Distributed generation (DG) and energy storage technology continue to be developed in power supply transformation. However, the difficulty of access to distributed power and battery energy storage stations makes the traditional distribution network planning method to be somewhat inadaptable. For this reason, this paper establishes a distribution network planning model with a power distribution station, substation, distribution network line, DG and battery energy storage station considered. The objective function of the model is to minimize the construction cost and maintenance cost during the distribution network planning period, and the constraint conditions take into consideration the operation reliability of the power system. Based on this, an improved multi-objective shuffled frog leaping algorithm (IMO-SLFA) was used for sample validation. According to the results, the model can effectively solve the expansion planning problem of a distribution network for several years, and then meet the access demand of DG and battery energy storage stations and the demand of load growth within a certain region. In a word, this paper has guiding significance for the long-term planning of a distribution network and the access of distributed power to the grid.

Keywords: DG, Battery Energy Storage Station, Distribution Network Planning.

1. Introduction
Recently, DG (distributed generation) has been rapidly developing, which effectively utilizes renewable energy by adjusting the peak-valley difference in the demands on the power grid and improves the reliability and flexibility of the overall power system. Therefore, DG will be one of the significant directions of development in the power industry in the twenty-first century (Li et al., 2012; Bao et al., 2012). However, among the DGs, there are some forms of renewable energy power generation which are intermittent and random. In view of this, the construction of supporting energy storage devices is essential to promote the reasonable consumption of distributed energy generation (Liu, 2012). The traditional planning method of a distribution network aims to design the expanded structure and capacity of the power grid according to the local load forecasting results and the existing power grid structure. It is designed to make the construction and operation economy of a distribution network to be most economical while meeting load growth demand and ensuring the safe operation of the power grid.
(Muñoz-Delgado et al., 2015). The difficulty access of DG and energy storage equipment causes the power supply and load type considered to change in the distribution network planning, which causes the traditional distribution network planning method to be not adaptive (Ganguly and Samajpati, 2015).

At present, there are many mathematical models with regard to distribution network planning, and some of them have considered DG and energy storage equipment. For example, an improved DG planning method based on a multi-objective hybrid quantum genetic algorithm was proposed, making the planning results more reasonable and feasible (Wang et al., 2011). An improved multi population genetic algorithm was applied to solve the multi-objective distribution network planning problem, and one concrete repair scheme for the infeasible solution generated by genetic operation was put forward (Ma and Cui, 2011). A distribution network planning model considering substations and feeder planning was established through improving the traditional genetic algorithm to resolve the model (Zidan et al., 2013). A microgrid model was proposed designed to improve the safety and stability of the power grid when human threat factors or natural disasters occur (Sheu et al., 2012). A distribution network planning model with DG considered was constructed, and was resolved by an extremal optimization algorithm (Lu et al., 2013). Based on these studies, new strategies were proposed to optimize the allocation of DG. The modeling and control of a storage battery/super capacitor hybrid energy storage system were studied to improve the power quality at the common connection point of the distribution network (Cao and Emadi, 2012). An optimization model for energy storage locating and sizing was established considering the voltage fluctuations of system node, load fluctuation, and the total capacity of energy storage system (Wu et al., 2014). Additionally, a multi-objective coordination planning model of distributed generation and an energy storage system with three objectives of economic cost, voltage quality and power surge in a local autonomous area of China was developed (Sheng and Liu, 2017).

However, most studies have only considered problems with DG or storage devices connected to the grid in the distribution network planning, and a large proportion of them only cover a one-year planning period. The distribution network planning model constructed in this paper, comprehensively considers newly built substations and distribution network lines, with DG and energy storage devices both connected to the distribution network, and extends the planning period to achieve medium and long term distribution network planning. This model is designed to provide decision support for the long term planning of a regional distribution network.

2. Model construction

The distribution network planning model comprehensively considering DG and the battery energy storage station is established in this paper. The objective function of the model is to minimize the total cost during the distribution network planning period with both construction cost and maintenance cost included. In the model, newly built substations and distribution network lines are considered to meet the needs of load growth in the distribution area in the foreseeable future. The model built is as follows.

2.1. Objective function

The objective function is as follows:

$$
Min F = Min(F_{co} + F_{PD} + F_{VL} - F_{C})
$$

(1)

Where \( F \) is the comprehensive objective; \( F_{co} \) is the construction and upgrading costs of the distribution network, including maintenance costs; \( F_{PD} \) is the operational costs of the distribution network, including the electricity cost of the substation, the reduced power generation cost due to the utilization of renewable energy, etc.; \( F_{VL} \) is the cost of lost load, which reflects power supply reliability; \( F_{C} \) is the renewable energy power generation subsidies provided by the government, mainly referring to the related benefits brought about by the renewable energy certificate trading mechanism in the electricity market.
2.1.1. The construction and upgrading costs of distribution network. The construction and upgrading costs of distribution network is calculated as follows:

\[ F_{CD} = F_{SS} + F_{FD} + F_{DG} + F_{RES} + F_{BES} \]  

(2)

Where FSS is the investment cost of the newly built substation; FFD is the investment cost of the newly built network line; FDG is the investment cost of newly built DG; FRES is the investment cost of newly built DG utilizing renewable energy; FBES is the investment cost of the newly built battery energy storage station.

In this paper, FSS, the investment costs of the various components in the distribution network, is divided into two categories: investment costs associated with the design capacity and investment costs not related to the design capacity. For example, the investment costs of building a new substation can be expressed as follows:

\[ F_{SS} = \sum_{i=1}^{I} C_i \left( P_{i,t}^{SS} \sigma_{i,t} + Q_{i,t}^{SS} M_{i,t}^{SS} \right) \]

(3)

\[ C_i = 1 / (1 + u)^{t-1} \]

(4)

\[ P_{i,t}^{SS} = F_i (1+s)^{-t} \left[ \frac{i(1+i)^h}{((1+i)^h-1)} + T_i \right] \frac{1}{\sum_{t'=1}^{T} (1+u)^{t'-n}} \]

(5)

\[ Q_{i,t}^{SS} = \left[ E_i (1+s)^{-t} \left( \frac{i(1+i)^h}{((1+i)^h-1)} + T_i \right) + O_i \right] \frac{1}{\sum_{t'=1}^{T} (1+u)^{t'-n}} + 8760 c_{SS_i,t}^{AVG} \sum_{t'=1}^{T} (1+u)^{t'-n} \]

(6)

Where, u is the internal rate of return; Ct is the present value factor which can discount the capital from the beginning of year t to the beginning of the planning period; Fi is the total amount of capital that is not related to the substation construction capacity in the initial investment; Ti is the relevant tax rate; i is the average interest rate in the life cycle of the substation; S is the annual growth rate of construction of investment costs; PSS i,t is the present value factor of the newly built substation costs that are independent of the substation capacity, and can reduce the capital in node i to year t; Ei is the equipment investment cost and construction cost related to the newly built substation capacity; Oi is the operation and operation cost of the substation; CSS i is hysteresis loss coefficient, and the unit is MW/MVA; cSS,AVG i,t is the energy loss cost of the substation; QSS i,t is the present value factor of the newly built substation costs that are related to the substation capacity, and can reduce the capital in node i to year t; σi,t is the decision variable designed to decide whether to build a new substation in node i in year t; MSS i,t is the capacity value of the newly built substation; ΩSS is the index set of the substation node.

FFD, FDG, FRES, FBES and FSS have the same derivation process and a similar form, so this paper will not repeat.

2.1.2. The operation costs of distribution network. In this paper, FPD, the operation cost of a distribution network, mainly considers the electricity purchase cost of the substation and the reduced power generation costs due to the utilization of renewable energy. The calculation formula is as follows:

\[ F_{PD} = P_{SSE} + P_{SSD} - P_{RES} + P_{DG} \]

(7)
Where PSSE is the electricity purchase cost of the substation; PSSD is extra expenses paid by power supply enterprises to power generation enterprises in the peak period; PRES is the reduced power purchase costs of DG utilizing renewable energy; PDG is the power purchase costs of DG utilizing traditional energy.

\[ P_{SS} = pf \sum_{i=1}^{T} \sum_{l \in SS} \left\{ \gamma l_{OFF} \epsilon_{i,l,OFF} SS_{OFF} + (1 - \gamma) h_{ON} \epsilon_{i,l,ON} SS_{ON} \right\} \]  \hspace{1cm} (8)

\[ P_{RES} = -\sum_{i=1}^{T} \sum_{l \in RES} \epsilon_{i,l,AVG} RG r_{RG} M_{RG} \]  \hspace{1cm} (9)

\[ P_{DG} = pf \sum_{i=1}^{T} \sum_{l \in DG} \epsilon_{i,l,DG} RG r_{DG} M_{DG} \]  \hspace{1cm} (10)

Where \( pf \) is the average power coefficient of the power grid; \( \gamma \) is the ratio of the period of low electricity consumption (valley) to the total duration of electricity consumption; \( l_{OFF} \), \( l_{ON} \) are the load factors of valley and peak periods in year \( t \), respectively; \( \epsilon_{i,l,OFF} \), \( \epsilon_{i,l,ON} \) are the power purchase prices of substation \( i \) in the valley and peak periods of year \( t \), respectively; \( S_{SSH,OFF} \), \( S_{SSH,ON} \) are the high voltage power supply capacities of the substation in the valley and peak periods of year \( t \); \( r_{RG} \) is the capacity coefficient of DG utilizing renewable energy, that is the ratio of the average power generation capacity to the designed installed capacity; \( \epsilon_{i,l,AVG} \) is the average power purchase cost at node \( i \) in the year \( t \); \( M_{RG} \) is the installed capacity of DG utilizing renewable energy at node \( i \) in the year \( t \).

2.1.3. The cost of lost load. The loss load factor \( V_{VL} \) is set to be a high value to avoid the occurrence of load shedding during the distribution operation. This can guarantee power supply reliability to some extent.

\[ F_{VL} = V_{VL} \sum \lambda \]  \hspace{1cm} (11)

Where \( V_{VL} \) is the loss load factor; \( \lambda \) is the non-supplied load.

2.1.4. Renewable energy power generation subsidies provided by the government. In this paper, \( F_{c} \), the renewable energy power generation subsidy provided by the government, is not a simple financial subsidy. It is a subsidy provided by the government issuing from the relevant policies and standards, providing certificates for renewable energy power generation that can be traded in the future open electricity market. Generally, 1MW of renewable energy power will earn one-unit certificate. The related mechanism of tradable energy certificates has been gradually matured in the European electricity market, and has provided a very positive incentive for the development of renewable energy. Referring to the relevant standards outside of China, the specific calculation formula is as follows:

\[ F_{c} = 8760 \sum_{i=1}^{T} \sum_{l \in RE} \epsilon_{i,l,REP} RG r_{DG} M_{RE} \]  \hspace{1cm} (12)

Whereas, \( \epsilon \) is the market transaction price of one unit certificate; \( r \) is the capacity factor for renewable energy generation; \( M \) is the installed capacity of renewable energy power generation.
2.2. Constraint conditions

2.2.1. Electric energy conservation constraints. For the existing substations of the distribution network:

\[
S_{i,t}^{SS,ON} = S_{i,t}^{SS,ON} + \frac{Z_{i}^{SS}(S_{i,t}^{SS,ON})^2}{V^2}
\]

(13)

\[
S_{i,t}^{SS,OFF} = S_{i,t}^{SS,OFF} + \frac{Z_{i}^{SS}(S_{i,t}^{SS,OFF})^2}{V^2}
\]

(14)

Where, \(Z_{i}^{SS}\) is the impedance of substation \(i\); \(v\) is the average grid voltage; \(S_{i,t}^{SS,ON}, S_{i,t}^{SS,OFF}\) are the output power of substation \(i\) during valley and peak hours respectively in year \(t\).

For all nodes in the grid:

\[
\sum_{j \in \Omega} S_{j,t}^{ON} - \sum_{j \in \Omega} (S_{j,t}^{ON} + Z_{ij}^{FR}(S_{j,t}^{OFF})^2) + S_{i,t}^{SS,ON} + S_{i,t}^{DG,ON} = S_{i,t}^{ON}
\]

(15)

\[
\sum_{j \in \Omega} S_{j,t}^{OFF} - \sum_{j \in \Omega} (S_{j,t}^{OFF} + Z_{ij}^{FR}(S_{j,t}^{ON})^2) + S_{i,t}^{SS,OFF} + S_{i,t}^{DG,OFF} = S_{i,t}^{OFF}
\]

(16)

Equations (15) and (16) respectively indicate the electric energy conservation equations during valley and peak hours, where \(S_{i,t}^{ON}\) is the apparent power value of node \(j\) inputs to node \(i\) by the transmission of line \(ij\); \(Z_{ij}^{FR}\) is the impedance value of line \(ij\); \(S_{i,t}^{ON}\) is the power demand of node \(i\) in year \(t\).

2.2.2. Capacity constraints. The capacity constraints are expressed as follows:

\[
0 \leq M_{i,t}^{SS} \leq U_{i}^{SS} \sigma_{i,t}^{SS}
\]

(17)

\[
0 \leq M_{i,t}^{DG} \leq U_{i}^{DG} \sigma_{i,t}^{DG}
\]

(18)

\[
0 \leq M_{i,t}^{RG} \leq U_{i}^{RG} \sigma_{i,t}^{RG}
\]

(19)

\[
0 \leq M_{ij,t}^{FR} \leq U_{ij}^{FR} \sigma_{i,t}^{FR}
\]

(20)

\[
0 \leq M_{i,t}^{BS} \leq U_{i}^{BS} \sigma_{i,t}^{FR}
\]

(21)

\[
S_{i,t}^{SS,ON} \leq \frac{1}{3} U_{i}^{SS}
\]

(22)

\[
S_{ij,t}^{ON} + S_{ji,t}^{ON} \leq \frac{1}{3} U_{ij}^{FR}
\]

(23)

Where \(M\) is the three-phase installed capacity of the components in the distribution network; \(U\) is the maximum three-phase installed capacity allowed to be installed at the node; \(\sigma\) is the binary decision variable.
2.2.3. **Node voltage constraints.** For the existing lines in distribution network:

\[ V_{i,t} = V_{j,t} + \frac{(S_{ij,t}^{ON} - S_{ji,t}^{ON})}{V_t} Z_{ij} \]  

(24)

Where \( V_{i,t} \) is the phase voltage value of node \( i \) in year \( t \); \( V_t \) is the average voltage amplitude in year \( t \).

For new lines in the distribution network:

\[ \begin{align*}
V_{ij,t} &\leq V_{j,t} + \frac{(S_{ij,t}^{ON} - S_{ji,t}^{ON})}{V_t} Z_{ij} + G \left[ 1 - \sum_{r \in \mathcal{R}_{ij,t}} \sigma_{r,t}^{FR} \right] \\
V_{ij,t} &\geq V_{j,t} + \frac{(S_{ij,t}^{ON} - S_{ji,t}^{ON})}{V_t} Z_{ij} - G \left[ 1 - \sum_{r \in \mathcal{R}_{ij,t}} \sigma_{r,t}^{FR} \right]
\end{align*} \]  

(25, 26)

Where \( G \) is the control variable; \( \sigma_{FR} \) is the decision variable (0-1 variable) of the newly built transmission line.

For all nodes in the distribution network:

\[ V_{\min} \leq V_{i,t} \leq V_{\max} \]  

(27)

Where \( V_{\min} \), \( V_{\max} \) are respectively the minimum and maximum value of the allowable phase voltage for the grid.

2.2.4. **Power grid security constraints.** For power generation security:

\[ \sum_{i \in \mathcal{N}} M_{i,0}^{SS} + \sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}} M_{i,t}^{SS} + \sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}} M_{i,t}^{DG} \geq 3 \mu_{\text{gen}} \sum_{i \in \mathcal{N}} S_{i,t}^{ON} \]  

(28)

Where, \( M_{i,0}^{SS} \) is the installed capacity of the current substation; \( M_{i,t}^{SS} \) is the installed capacity of the new substation; \( M_{i,t}^{DG} \) is the installed capacity of new distributed power; \( S_{i,t}^{ON} \) is the demand capacity for node \( k \) in peak hours; \( \mu_{\text{gen}} \) is the safety factor for generation, whose value is between 1.2~1.3;

Transmission line security constraints are:

\[ m_{j,0} + \sum_{i \in \mathcal{N}} \sum_{r \in \mathcal{R}} \sigma_{r,i}^{FR} \geq m_{j,i} \]  

(29)

Where \( m_{j,0} \) is the number of lines connected to node \( j \) in the initial phase; \( m_{j,i} \) is the number of lines connected to node \( j \) in year \( t \).

2.2.5. **Battery energy storage station balance constraint.** The constraint of the battery energy storage station balance is expressed as follows:

\[ S_{i,t}^{BS,OFF} = \frac{(1-\gamma)}{\gamma \eta_i} S_{i,t}^{BS,ON} \]  

(30)

Where \( \gamma \) is the proportion of the period of low (valley) power consumption to the total power consumption duration; \( \eta_i \) is the energy storage efficiency of the battery energy storage station.
2.2.6. Other constraints. These constraints are ensure that in the planning period, only one new substation, one distributed generation and one line can be constructed or erected between any two nodes.

\[ \sum_{t=1}^{T} \sigma_{ij,SS} \leq 1, \text{ for } \forall i \in \Omega_{SSnew} \]  
\[ \sum_{t=1}^{T} \sigma_{ij,FR} \leq 1, \text{ for } \forall ij \in \Omega_{FRnew} \]  
\[ \sum_{t=1}^{T} \sigma_{ij,DG} \leq 1, \text{ for } \forall i \in \Omega_{DGnew} \]  
\[ \sum_{t=1}^{T} \sigma_{ij,RG} \leq 1, \text{ for } \forall i \in \Omega_{RGnew} \]  
\[ \sum_{t=1}^{T} \sigma_{ij,BS} \leq 1, \text{ for } \forall i \in \Omega_{BSnew} \]  

Where, \( \sigma \) is the binary decision variable; \( \Omega_{SSnew}, \Omega_{FRnew}, \Omega_{DGnew}, \Omega_{RGnew}, \) and \( \Omega_{BSnew} \), are the node index sets of the newly built substation, transmission lines, distributed generation, renewable energy power and battery energy storage station, respectively.

3. Imo-slf

3.1. Mechanism and procedure of SFLA

The shuffled frog leaping algorithm (SFLA) is a heuristic population evolutionary algorithm based on a global collaborative search. The algorithm uses a heuristic function (any mathematical functions) for a heuristic search, designed to find solutions of combinatorial optimization problems. The algorithm has the advantages of having a simple concept, few adjustment parameters, fast calculation speed, strong capability of global search optimization and easy realization (Dai et al., 2012).

The leapfrog algorithm originated from the research on frog foraging behavior. The basic idea is based on the behavior of a frog population living in a wetland scattered with many stones. The frogs leap among various rocks to find the maximum amount of food with the minimum of steps. Each frog has its own solution to this problem (self-solution) and can exchange its self-solution information with other frogs to enhance the whole population's ability to find food, resulting in global optimization (Luo et al., 2009). The execution of the algorithm is divided into several steps. First, the entire frog population is divided into different sub populations, and each sub population is called a memeplex, each having its own self-solution, and carrying out local search strategies, respectively. Each individual in the sub population having its own self-solution, interacts with other individuals and makes full use of memetic evolution to develop. When the sub population evolves to a certain stage, various sub populations begin to exchange information (global information exchange) to realize mixed operations among sub populations, until the set conditions are meet (Zhang et al., 2013).

The SFLA parameters mainly include: \( F \) is the total number of the frog population; \( m \) is the number of memeplexes; \( n \) is number of frogs in each memeplex; \( S_{max} \) is the maximum allowable jumping step; \( P_x \) is global optimal solution; \( P_b \) is local optimal solution; \( P_w \) is local worst solution; \( q \) is the number of frogs in a sub population; \( L_S \) is the local element evolution times; \( S_F \) is the number of global information exchanges. The steps of the standard leapfrog algorithm are as follows:

(1) Global exploration

Step 0: Initialization. Randomly generate an initial frog population \( F \) in the feasible domain, and determine \( m \) and \( n \). Then the number of frogs in the whole population can be calculated by \( F = m \times n \).
Step 1: Generating a virtual population. In the feasible solution space \( \Omega \subset \mathbb{R}^n \), generate \( F \) frogs, expressed as \( U(1), U(2), \ldots, U(F) \). \( n \) is a dimensional variable, \( U(1), U(2), \ldots, U(F) \) represent candidate solutions of the optimization problem in the solution space. The coordinate of frog \( i \) in \( n \)-dimensional space is \( U(i) = (U_{i1}, U_{i2}, \ldots, U_{in}) \). The performance of \( U(i) \) is expressed by \( f(i) \).

Step 2: Classification of frogs. Arrange \( F \) frogs in descending order according to fitness, and produce an array \( X = \{U(i), f(i), i=1,2,\ldots,F\} \) where \( i=1 \) shows that the frog is in the best position (most fit). Then record the best frog's position \( P_g = U(1) \).

Step 3: The frogs are grouped into various memeplexes. The array \( X \) is divided into \( m \) memeplexes: \( Y_1, Y_2, \ldots, Y_m \). Each memeplex has \( n \) frogs, that is \( Y_k = \{U(j), f(j) \mid U(j) = U(k+m(j-1)), f(j) = f(k+m(j-1)), j=1,\ldots,n\} \), of which \( k=1,2,\ldots, m \).

Step 4: Each memeplex performs memetic evolution. In each population, every frog can be affected by other frogs, and can evolve through memetic evolution to gradually approach the target position (global optimization).

(2) Local exploration

Step 4-0: Set \( i_m = 0 \). \( i_m \) indicates the number of memeplexes, varying between 0 and \( m \). Set \( i_N = 0 \). \( i_N \) represents the number of evolutions, compared with the allowed maximum evolution number \( N \) of memeplex. \( P_b \) and \( P_w \) respectively represent the most fit and least fit (best and worst) frogs of each memeplex, and \( P_g \) represents the best frog in the whole population. Each evolution of sub populations can only improve the location of the worst frog \( P_w \), but cannot improve the worst frog of the whole population.

Step 4-1: \( i_m = i_m + 1 \).

Step 4-2: \( i_N = i_N + 1 \).

Step 4-3: Adjust the worst frog's position using the adjustment method as follows:
Frog moving distance \( D_i = \text{rand}() \times (P_b - P_w) \)
The new position \( P_w = P_w + D_i \) (\( D_{max} \geq D_i \geq -D_{max} \))
where \( \text{rand}() \) is a random number between 0 and 1, \( D_{max} \) is the maximum distance allowed for a frog to move.

Step 4-4: If the implementation of the above operations can obtain a better position of the frog, i.e., can produce a better solution, then the new-position frog replaces the original frog. Otherwise, \( P_g \) is used instead of \( P_w \), and the above process is repeated.

Step 4-5: If the above method still cannot generate a better position of the frog, then randomly generate a new solution to replace the original position of the worst frog \( P_w \).

Step 4-6: If \( i_N < N \), then perform 4-2

Step 4-7: If \( i_m < m \), then perform 4-1.

Step 5: Frogs jump between populations. After performing a certain memetic evolution in each memeplex, each sub population \( Y_1, Y_2, \ldots, Y_m \) must merge into \( X \); that is \( X = \{Y_k, k=1,2,\ldots,m\} \). Then, \( X \) is arranged in descending order according to fitness, and update the best frog \( P_g \) of the population.

Step 6: Termination condition. If the iteration termination condition is satisfied, the search will stop. Otherwise, execute step 3. Generally, when a certain number of cyclic evolutions have been performed, the frog that represents the best solution no longer changes, and the search is stopped. The maximum number of evolutions can be defined as the standard for algorithm termination.

3.2. Improved Multi-objective Shuffled Frog Leaping Algorithm (IMO-SLFA)

From the perspective of SFLA steps, SFLA is of clear logical framework. However, because SLFA uses Equations (15) and (16) for a local search, when there are no better frogs can be found, one frog randomly generated in the search space is used to continue the optimization process. But at this time, a situation may arise where the new frog is not as good as the worst frog. In view of this, the Random Nelder Mead (RNM) is used to improve the local search capability of SLFA, and then to effectively avoid the above problem by presenting to the decision-maker many representative non-inferior solutions. The RNM is the improvement of Nelder Mead, which can make the search direction more accurate, and
more effectively determine the potential replacement points near the search direction. The IMO-SLFA process is shown in Figure 1.

When using IMO-SFLA to solve the joint optimization model of distributed generation and distribution network planning, the practical significance of the frog in SFLA must be made clear. It can be seen from the elaboration above that the algorithm makes distributed generation owners (DGO) and distribution network operators (DNO) achieve a optimal state and realizes emission reduction targets by determining the unit type, investment time, location and capacity of DG, and the construction of the distribution network lines and substations. Therefore, the frog of SFLA in this paper indicates the optimal position and state of the DG and distribution network, and the individual fitness of the frog corresponds to the function value of the problem's objective function.

4. Example and result analysis

The initial distribution network of the case in this paper has 11 nodes and nine 25kV transmission lines, which need to be expanded into 16 nodes and 16 transmission lines with DG and renewable energy generation included. The initial grid structure is shown in Figure 2.

This paper assumes the following conditions: the expansion planning period of the distribution network is five years; the load growth rate of the load node is 4%; the service life of the substation, transmission line, DG and renewable energy power supply are 30 years, 30 years 15 years and 10 years, respectively; the market transaction price of renewable energy generation certificates is 700 yuan /MWh; the maximum permitted voltage drop rate of the load node is 5%; the maximum load of substations and transmission lines cannot be more than 10% of their rated capacity; the annual average rising rate of the energy price is 5%; the annual rising rate of substations and transmission lines cannot be more than 10% of their rated capacity; the annual average rising rate of the energy price is 5%; the annual rising rate of construction and equipment cost is 7%; the internal rate of return is 10%; the tax rate is 3%; the bank interest rate is 8% per year.

The technical parameters and construction cost of each component in the distribution network are shown in Table 1-Table 12.

According to the parameters and the load variations of each node and the linearization of the constraint conditions, IMO-SLFA is applied and Matlab software is used for numerical simulation. The calculated distribution network expansion decision is shown in Table 13, where $M_{XX}^{I,t}$ represents the capacity of the components in the distribution network; XX is the component type represented by variables; I is the number in a certain kind of component; t is the construction time.
Start

Initialization: memplex quantity \((n=0)\), the number of frogs in a memplex, the number of iterations in a memplex \((n=0)\), and randomly generate an initial frog population.

Arrange frogs in descending order according to the value of \(f(i)\) and group them into different memplexes in turns.

\[ i_{m} = 1 \]

\[ i_{w} = 1 \]

Find out \(P_{b}, P_{w}\) and \(P_{g}\), and calculate (22) & (23).

Yes \(P_{w}^{'}\) is better than \(P_{w}\)

No

Use \(P_{g}\) to instead of \(P_{b}\) and calculate (22) & (23).

Yes \(P_{w}^{'}\) is better than \(P_{w}\)

No

Generate a new solution \(P_{w}^{'}\) using random Nelder Mead.

Replace \(P_{w}\) with the new solution \(P_{w}^{'}\).

\[ i_{w} = N \]

No

Yes

Next memplex: \(i_{w} = i_{w} + 1\)

\[ i_{w} = m \]

No

Yes

Memplex sets.

Termination criterion satisfied.

No

Yes

Output the Pareto optimal solution.

Figure 1. The flowchart of IMO-SFLA
The existing substations

The substations that have been planned

The existing lines

The Lines that have been planned

Table 1. Operating parameters of the substations that have been built

| Substation number / The node number | SS1/1 | SS2/2 |
|------------------------------------|-------|-------|
| Rated capacity of transformer (MVA/ Three-phase) | 223   | 43    |
| Current maximum load (MVA/ Three-phase) | 39.696 | 6.966 |
| Impedance (%)                      | 6.15  | 5.0   |
| Iron loss (MW/MVA)                 | 0.0337| 0.0305|

Table 2. Electricity purchase cost of the substations that have been built

| Substation | Prices in the peak periods(yuan/MWh) | Average peak-valley price radio |
|------------|--------------------------------------|---------------------------------|
| SS 1       | 349.32                               | 0.635                           |
| SS 2       | 282.9                                | 0.610                           |

Figure 2. The initial grid structures
### Table 3. Various load node parameters

| The load node number / The node number | Electricity demand in peak periods (MVA/Single-phase) | Valley-peak power consumption length radio | Electricity load factor in peak periods | Electricity load factor in valley periods | Power factor |
|---------------------------------------|-----------------------------------------------------|------------------------------------------|----------------------------------------|-------------------------------------------|-------------|
| DL1/3                                 | 1.930                                               | 0.630                                    | 0.447                                  | 0.656                                     | 0.922       |
| DL2/4                                 | 2.467                                               | 0.620                                    | 0.375                                  | 0.741                                     | 0.847       |
| DL3/5                                 | 2.812                                               | 0.525                                    | 0.621                                  | 0.632                                     | 0.945       |
| DL4/6                                 | 2.848                                               | 0.571                                    | 0.347                                  | 0.740                                     | 0.875       |
| DL5/7                                 | 1.581                                               | 0.521                                    | 0.422                                  | 0.674                                     | 0.936       |
| DL6/8                                 | 1.564                                               | 0.738                                    | 0.488                                  | 0.625                                     | 0.844       |
| DL7/9                                 | 1.811                                               | 0.664                                    | 0.612                                  | 0.631                                     | 0.969       |
| DL8/10                                | 0.333                                               | 0.622                                    | 0.483                                  | 0.671                                     | 0.954       |
| DL9/11                                | 0.148                                               | 0.687                                    | 0.391                                  | 0.710                                     | 0.919       |

### Table 4. Operating parameters and cost of the existing substations

| Substation number/The node number | Fixed cost of initial investment (yuan) | Costs of equipment and installation (yuan/MVA) | Tax rate per year (%) | Annual operating and maintenance costs(yuan/MVA) | Maximum allowable installation capacity (MVA/Three-phase) | Transformer impedance (%) | Iron loss (MW/MVA) |
|-----------------------------------|----------------------------------------|-----------------------------------------------|-----------------------|-------------------------------------------------|----------------------------------------------------------|---------------------------|-------------------|
| SS3/12                            | 4,215,210                              | 222,882                                      | 5                     | 31,543                                          | 20                                                        | 4.8                       | 0.03              |
| SS4/13                            | 6,055,905                              | 180,576                                      | 5                     | 36,217                                          | 20                                                        | 4.8                       | 0.03              |

### Table 5. Electricity purchase cost of the substations that have been planned

| Substation | Prices in peak periods(yuan/MWh) | Average peak-valley price radio |
|------------|----------------------------------|---------------------------------|
| SS 3       | 319.185                          | 0.627                           |
| SS 4       | 322.875                          | 0.663                           |

### Table 6. Various possible load node parameters

| The load node number / The node number | Electricity demand in peak periods (MVA/Single-phase) | Valley-peak power consumption length radio | Electricity load factor in peak periods | Electricity load factor in valley periods | Power factor |
|---------------------------------------|-----------------------------------------------------|------------------------------------------|----------------------------------------|-------------------------------------------|-------------|
| DL10/14                               | 0.321                                               | 0.483                                    | 0.452                                  | 0.754                                     | 0.88        |
| DL11/15                               | 0.557                                               | 0.541                                    | 0.389                                  | 0.655                                     | 0.93        |
| DL12/16                               | 0.081                                               | 0.617                                    | 0.537                                  | 0.931                                     | 0.90        |

### Table 7. Various parameters of the transmission lines that have been built

| Line number | Line length(km) | Current maximum load (MVA/Single-phase) | Maximum capacity (MVA/Single-phase) | Resistance (ohm/km) | Reactance(ohm/km) |
|-------------|-----------------|----------------------------------------|-------------------------------------|---------------------|-------------------|
| FR1         | 5.8400          | 1.581                                  | 2.65                                | 3.690               | 0.545             |
| FR2         | 3.8045          | 2.397                                  | 3.45                                | 1.589               | 0.517             |
| FR3         | 2.6104          | 5.296                                  | 5.70                                | 0.476               | 0.439             |
| FR4         | 1.1885          | 2.782                                  | 3.85                                | 0.958               | 0.471             |
| FR5         | 2.0008          | 3.391                                  | 3.85                                | 0.958               | 0.471             |
| FR6         | 3.5189          | 1.611                                  | 2.15                                | 3.692               | 0.541             |
| FR7         | 3.3779          | 0.353                                  | 1.50                                | 5.861               | 0.558             |
| FR8         | 2.1626          | 0.523                                  | 1.50                                | 5.861               | 0.558             |
| FR9         | 1.8472          | 1.819                                  | 3.45                                | 1.588               | 0.520             |
Table 8. Construction cost of the transmission lines that have been planned

| Line number | Fixed cost of initial investment(yuan/km) | Costs of equipment and installation (yuan/MVA-km) | Tax rate per year (%) | Annual operating and maintenance costs(yuan/km) |
|-------------|------------------------------------------|-----------------------------------------------|----------------------|-----------------------------------------------|
| FR10        | 57,760                                   | 4,473                                         | 5                    | 2,521.7                                       |
| FR11        | 49,919                                   | 5,939                                         | 5                    | 2,089.2                                       |
| FR12        | 69,330                                   | 5,462                                         | 5                    | 3,442.5                                       |
| FR13        | 56,584                                   | 6,304                                         | 5                    | 2,426.3                                       |
| FR14        | 53,766                                   | 3,944                                         | 5                    | 3,133.8                                       |
| FR15        | 42,866                                   | 4,966                                         | 5                    | 2,426.3                                       |
| FR16        | 74,826                                   | 5,639                                         | 5                    | 3,464.9                                       |

Table 9. Various initial parameters of the transmission lines that have been planned

| Line number | Line length(km) | Maximum allowable installation capacity (MVA/Three-phase) | Resistance (ohm/km) | Reactance(ohm/km) |
|-------------|-----------------|----------------------------------------------------------|---------------------|-------------------|
| FR10        | 6.6790          | 15                                                       | 2.743               | 0.514             |
| FR11        | 5.0096          | 15                                                       | 2.743               | 0.514             |
| FR12        | 3.8707          | 15                                                       | 2.743               | 0.514             |
| FR13        | 1.5022          | 15                                                       | 2.743               | 0.514             |
| FR14        | 1.8474          | 15                                                       | 2.743               | 0.514             |
| FR15        | 4.4163          | 15                                                       | 2.743               | 0.514             |
| FR16        | 5.6113          | 15                                                       | 2.743               | 0.514             |

Table 10. Cost of the distributed generation that have been planned to use traditional energy

| DG number/The node number | Fixed cost of initial investment (yuan) | Costs of equipment and installation (yuan/MVA) | Tax rate per year (%) | Annual operating and maintenance costs (yuan/MVA) | Maximum installed capacity (MVA/Three-phase) | Fuel cost(yuan/MWh) |
|---------------------------|----------------------------------------|----------------------------------------------|----------------------|-------------------------------------------------|-----------------------------------------------|-------------------|
| DG1/4                     | 327,610                                | 4,175,136                                    | 5                    | 56,211                                          | 5                                             | 190.65            |
| DG2/8                     | 586,833                                | 5,249,972                                    | 5                    | 74,163                                          | 3                                             | 172.20            |
| DG3/9                     | 369,369                                | 4,891,944                                    | 5                    | 64,944                                          | 10                                            | 215.25            |

Table 11. Cost of the distributed generation that have been planned to use renewable energy

| DG number/The node number | Fixed cost of initial investment (yuan) | Costs of equipment and installation (yuan/MVA) | Tax rate per year (%) | Annual operating and maintenance costs (yuan/MVA) | Maximum installed capacity (MVA/Three-phase) | Capacity factor |
|---------------------------|----------------------------------------|----------------------------------------------|----------------------|-------------------------------------------------|-----------------------------------------------|-----------------|
| RG1/7                     | 677,435                                | 7,622,439                                    | 0                    | 27,503                                          | 0.5                                           | 0.571           |

Table 12. Parameters and cost of the bs that has been planned

| BS number/The node number | Fixed cost of initial investment(yuan) | Costs of equipment and installation (yuan/MVA) | Tax rate per year (%) | Annual operating and maintenance costs(yuan/MVA) | Maximum installed capacity (MVA/Three-phase) | Energy storage efficiency (%) |
|---------------------------|----------------------------------------|----------------------------------------------|----------------------|-------------------------------------------------|-----------------------------------------------|-----------------------------|
| BS1/7                     | 528,568                                | 2,637,710                                    | 5                    | 58,425                                          | 2.5                                           | 78                          |

Table 13. Distribution network expansion decision

| Decision variables | Designing installation capacity (Three-phase) |
|--------------------|-----------------------------------------------|
| $M^c_1$            | 0.5MVA                                        |
| $M^c_2$            | 2.1MVA                                        |
| $M^c_3$            | 6MVA                                          |
| $M^c_4$            | 6.5MVA                                        |
| $M^c_5$            | 4.5MVA                                        |
| $M^c_6$            | 4.5MVA                                        |
| $M^c_7$            | 1.875MVA                                      |
| $M^c_8$            | 1.875MVA                                      |
| $M^c_9$            | 1.875MVA                                      |
Whereas, $M_{XX}$ represents the capacity of the components in distribution network; XX means the component type represented by variables; I is the number in a certain kind of component; t is the construction time.

The extended distribution network structure at the end of the planning period is shown in Figure 3.

![Figure 3. The extended distribution network structure](image)

The various costs of the final objective function are shown in Table 14.

| Projects                              | Cost (yuan) |
|---------------------------------------|-------------|
| $F_{new}$ The new-built substation    | 5,350,746   |
| $F_{new}$ The new-built network line  | 976,725     |
| $F_{res}$ Renewable energy power generation | 2,846,736 |
| $F_{new}$ The new-built battery energy storage station | 70,513,200 |
| $P_{pse}$ The reduced electricity purchase cost of the substation | 218,706,841 |
| $F_{res}$ The reduced electricity purchase cost because of the utilization of renewable energy | 3,062,651 |
| $F_{c}$ The renewable energy power generation subsidies | 6,368,651 |
| Sum                                   | 288,962,946 |

### 5. Conclusion

This paper studies the planning method of distribution network planning with power storage and distributed generation, and establishes the model with the objective of costs minimization of the distribution network system, and comprehensive constraints take into consideration the system operation reliability and capacity balance. The improved shuffled frog leaping algorithm is used to solve the problem. In summary, this paper provides a useful guide for future distribution network planning.
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