The comprehensive planning method of distribution network considering DG and energy storage facilities

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Abstract. The development of distributed generation and battery energy storage station make the traditional power distribution network planning method be inapplicable. To solve this problem, we establish a distribution network planning model comprehensively considered distribution network lines, distributed generation and the energy storage facilities. We use the construction cost and operation maintenance cost minimum during the distribution network planning period as objective function, system operation reliable as well as other system operation constraints as constraint conditions, and take advantage of the results of load forecasting to build the model. This paper has certain guiding significance for the long-term planning of the distribution network and distributed generation.

Keywords: distributed generation, energy storage facilities, distribution network planning.

1. Introduction
In recent years, distributed generation (DG) has been rapidly developed. DG has become an important development direction of the current power industry. Because DG can realize the efficient use of renewable energy, and the regulation is flexible, which can meet system requirements such as peak clipping and valley filling [1]. However, DG due to renewable energy have intermittent and random characteristics. In order to eliminate the impact of DG’ intermittent and random characteristics, it is necessary to support energy storage facilities [2]. The traditional distribution network planning method is to rationally design and extend the structure and capacity of the power grid according to the local load forecasting results and the existing power grid structure within a certain planning period, so that the construction and operation economy of the distribution network is optimal [3]. The access of distributed generation and energy storage equipment makes the situation of distribution network planning more complicated, and the traditional distribution network planning method has certain incompatibility [4].

At present, most of the literature only considers distribution network planning problems when distributed power or energy storage facilities are connected to the grid within a short planning period. The distribution network planning model constructed in this paper considers components such as new substation, new line, DG and energy storage facilities. The model also considers the time value of distribution network construction and operation and maintenance costs, extends the planning period, and is suitable for medium and long-term planning of distribution networks.
2. Planning Model
The distribution network planning model constructed in this paper takes the minimum total cost during the planning period as the objective function.

The model aims at the minimum total investment during the planning period, taking into account the investment and operating costs of distributed generation, the investment costs and construction costs (including lines and substations) required for system upgrades, the investment costs of alternative capacitors, and installation costs for energy storage facilities. The objective function is shown in equation (1).

\[
\min \ J = C_{DG}^i + C_i + C_{ES} + C^{yp} \\
+ \frac{1}{T}\sum_{b=1}^{T} \left( \sum_{i=1}^{n} C_{DG}^i P_{DG}^i + \sum_{m,n=2}^{n} C_{DG,0} M_{DG} M_{DG} \right) \left( 1 + \frac{y}{d} \right)^y \\
+ \sum_{i=1}^{n} \sum_{j=1}^{n} \left( C_{ES} G_{ij} L_{ij} \right) \frac{1}{y} \left( 1 + \frac{y}{d} \right)^y \\
+ \sum_{i=1}^{n} \left( C_{Cap} \right) \left( 1 + \frac{y}{d} \right)^y \\
+ \frac{y}{y} \sum_{i=1}^{n} \sum_{j=1}^{n} \left( P_{ES} \right) \left( 1 + \frac{y}{d} \right)^y \\
+ \frac{y}{y} \sum_{i=1}^{n} \sum_{j=1}^{n} \left( P_{ES} \right) \left( 1 + \frac{y}{d} \right)^y \\
\]

In equation: \( C_{DG}^i \) represents the investment and operating expenses of DG during the planning period, yuan; \( i \) represents the total number of nodes; \( d \) represents the discount rate; \( T \) represents total number of years in the planning period; \( y \) represents the yth year of the planning period; \( B \) represents total number of load segments; \( b \) represents the bth number of load segments. \( C_{DG,F}^i \) represents annual unit investment cost of DG, yuan/MW; \( P_{DG}^i \) represents DG capacity at node \( i \), MW; \( C_{DG,0}^i \) represents annual operating costs of DG, yuan/MW; \( P_{DG,0}^i \) represents output power of DG at node \( i \) load in section \( b \), MW; \( h_b \) represents DG annual operating hours in section \( b \); \( C^F \) represents investment costs and construction costs required for upgrading the line, yuan/MW; \( j \) represents the \( jth \) node; \( C_{Cap} \) represents annual fixed investment cost of the line, yuan; \( G_{ij} \) represents geographical cost factors for the line between node \( i \) and node \( j \); \( L_{ij} \) represents the length of line between node \( i \) and node \( j \), km; \( Z^i_{CAP} \) represents the boolean variable for line upgrade, (0/1); \( C_{Cap} \) represents the investment cost of alternative capacitors, yuan; \( C^S \) represents unit annual investment cost of shunt capacitor, yuan/MVAr; \( Q_{Cap}^i \) represents capacitor capacity at node \( i \), MVAr; \( z^S \) is a boolean variable, represents whether the energy storage facility is installed at node \( i \); \( P_{ES}^i \) represents energy storage capacity installed in node \( i \); \( c_y \) represents total cost of energy storage facilities per unit capacity during the planning period. Where \( c_y \) represents the purchase cost per unit capacity, yuan; \( M_c \) represents annual maintenance cost per unit capacity, yuan.

Constraints:
1) System Constraints
System constraints such as power flow constraints, line capacity constraints, and node voltage constraints are described in Reference [5].

2) DG Capacity Constraint
The active and reactive power of the DG unit are limited by its maximum capacity, as shown in equation (2) and (3).

\[
P_{DG,0}^{min} \leq P_{DG,0}^i \leq P_{DG,0}^{max} \\
Q_{DG,0}^{min} \leq Q_{DG,0}^i \leq Q_{DG,0}^{max} \\
\]

In equation: \( P_{DG,0}^i \) and \( Q_{DG,0}^i \) represents active and reactive power of DG at node \( i \) load in section \( b \) respectively, MW and MVAr; \( P_{DG,0}^{min} \) and \( P_{DG,0}^{max} \) represents the lower and upper limits of DG active power respectively, MW; \( Q_{DG,0}^{min} \) and \( Q_{DG,0}^{max} \) represents the lower and upper limits of DG reactive power respectively, MVAr.

3) Energy Balance Constraint of Energy Storage Facility
The energy storage device must be able to achieve charge and discharge to track rapid changes in load. Limited by technical conditions, the battery charging and discharging capacity and rate must meet...
certain constraints in actual operation. The relevant formulas and parameters are described in the literature [6].

3. IMO-SFLA
In this paper, the improved multi-objective shuffled frog leaping algorithm (IMO-SFLA) is used to solve the model. IMO-SFLA is a new type of heuristic population evolution algorithm based on global collaborative search. It performs a heuristic search through a heuristic function to find a solution to the combinatorial optimization problem. The algorithm has the characteristics of simple concept, less adjustment parameters, fast calculation speed, strong global search and optimization ability, and easy implementation. Specific algorithm descriptions and steps are described in the reference [7].

4. Examples and results analysis
In order to verify the rationality of the proposed planning method in this paper, this section analyzes an example of an IEEE 33-node system. The system contains 33 nodes in the radial configuration. There are 2 transformers at node 0, one of which has a variable capacity of 15 MV•A and the other is 16 MV•A. The peak demand for active load of the system is 37 MW, and the peak load of reactive power is 15.7 Mvar. Before the upgrade, the active power loss of the distribution network system is 2.4 MW, and the system voltage stability index is 0.61. Other relevant parameters of the network can be found in the literature [8].

Assume that the expansion planning period of the distribution network is 10 years; the load growth rate of each load node is 4%; the service life of the substation and transmission line is 30 years; the service life of the distributed power supply is 15 years; the maximum voltage allowed by the load node Reduced to 5%; internal rate of return is 8%.

This article sets three scenarios: Scenario 1 is a planning scheme developed using a model constructed by this paper; Scenario 2 does not consider energy storage facilities; Scenario 3 is to use the traditional planning model to develop a planning scheme, which is without considering energy storage and DG. The three scenarios are respectively solved by IMO-SLFA, and the simulation results of Matlab software are shown in Table 2 and Table 3. It should be noted that the data of energy storage and DG shows the capacity in parentheses, and the nodes outside the brackets.

Tab. 1 Operating parameters and costs of each system component

| component | Fixed cost of initial investment yuan/MVA | Equipment installation cost yuan/MVA | Annual operating costs yuan/MVA | Single node maximum allowable capacity MVA/ MW |
|-----------|------------------------------------------|--------------------------------------|---------------------------------|-----------------------------------------------|
| Substations | 4,152,800 | 213,266 | 30,425 | 20 |
| DG | 677,435 | 7,622,439 | 27,503 | 5 |
| ES | 528,568 | 2,637,710 | 58,425 | 2.5 |
| Lines | 49,919 | 5,939 | 3,442 | - |

Fig. 1 Standard 33-bus radial distribution system
The distribution network planning model constructed in this paper is based on the traditional distribution network planning model, considering the impact of DG and ES component access on the distribution network. The model takes the construction network construction cost as the objective function to minimize the constraints of line capacity, node voltage and DG capacity. The model is divided into multiple scenarios to verify the model simulation results, which provides a reference for the establishment of a comprehensive distribution network planning decision support system.

5. Conclusion

It can be seen that scenario 1 has the highest fixed investment, but the annual purchase of large grid power and annual loss load hours is the least, and the voltage stability is the highest. Scenario 2 and Scenario 3 have relatively few fixed investments, but in order to ensure the normal operation of the system, the required purchased electricity and lost load hours have increased, resulting in an increase in operating costs of 23.84 million yuan and 19.68 million yuan respectively.

As shown in Table 2 and Table 3, the scenario plan 1 requires a fixed asset investment of 71.290 million yuan, which is the highest of the three scenarios. The annual net power of Scenario 1 is 175.72 MW·h, and the annual loss load hours are 2.11 h, which is the least under the three scenarios. This results in a significant reduction in the operating costs of Scenario 1. In addition, the voltage stability index of scenario 1 is also the highest, reflecting the stability of the system after planning. The fixed investment in Scenario 2 decreased by 9.3% compared with Scenario 1, but the annual purchase of large grid power increased by 44 MW·h. Due to the lack of energy storage facilities, the volatility of DG causes the annual loss load hours to reach 2.93 h/year. The fixed investment in Scenario 3 decreased by 12.3% compared with Scenario 1, but the annual purchase of large grid power increased by 181.24 MW·h. The three-year loss load hour of the scenario is 2.83 h/year, which is 0.54 h/year more than scenario 1, and the voltage stability coefficient is the lowest. According to the various operating costs, the scenario 2 and scenario 3 planning periods will increase operating costs by 23.84 million yuan and 19.68 million yuan respectively.
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