A bi-level model for distributed generation optimal operating considering benefits of park power distribution company

Shuo Yin¹, Shiqian Wang¹, Meng Yang¹, Fengkai Qiu²*, Jialin Lin ², Shuo Zhang²

¹ Economic Research Institute of State Grid Henan Electric Power Company, Zhengzhou, China
² School of economics and management, North China Electric Power University, Beijing, China

*Corresponding author e-mail: 120192206983@ncepu.edu.cn

Abstract. Distributed power generation market transactions provide a new profit model for park power distribution companies, which stimulates its enthusiasm for investing in distributed generation (DG). This paper integrates the investment income of distributed generation and the operation strategy of the park power distribution company into a bi-level programming problem. The improved particle swarm optimization algorithm is used to solve the model. The results show that the model can increase the comprehensive income of the distribution company, formulate a reasonable DG contract price and interruptible load compensation price, and effectively guide the planning and configuration of distributed generation and the economic efficiency of power distribution companies.

1. Introduction

In October 2016, the National Development and Reform Commission and the National Energy Administration further promulgated the "Administrative Measures for Orderly Liberalization of Distribution Network Business", which proposed to open the distribution network business in an orderly manner, encourage social capital to invest, construct and operate the incremental distribution network, and provide users with safe, convenient and fast power supply services through competitive innovation[1]. In the past four years of reform, the pilot scope of incremental power distribution projects has gradually expanded. The National Development and Reform Commission and the National Energy Administration have approved five batches of 483 incremental power distribution. In the competition, the distribution companies in the incremental distribution park attract power users, increase market share and ensure enterprise income through value-added services such as distributed energy (DG), which has become the core business of each power selling entity [2]. However, the integration of DG into the power grid has many effects on the stable operation of the distribution network in terms of power flow, voltage, harmonics, etc. These effects are inseparable from the location, capacity, and operation mode of DG [3]. Therefore, the planning and operation of the distribution network system and the DG is a hot area of academic research in recent years. On the basis of analyzing the operating mode of power distribution companies in the market environment, this paper establishes a bi-level programming model that considers the revenue of power distribution companies.
2. Model construction

2.1. Model framework and related assumptions

As the construction and operator of distribution network, power distribution companies should consider not only the benefits of DG access to the distribution network, but also the investment cost of DG and its corresponding power sales mode when investing in DG. The operation mode of power distribution company in the electricity market environment is shown in Figure 1.

![Figure 1. Operation mode of power distribution company](image)

At present, the main types of DG investments are wind power (WG), photovoltaic (PV), and micro gas turbine (MT). As the leader of DG construction, power distribution companies must consider both the economics of investment and the operating income after the DG is connected when selecting the location and capacity of the DG. The bi-level programming model proposed in this paper is described as follows.

1) Upper-level model. The location and capacity of DG are determined with the maximum NPV of comprehensive income as the optimization objective.

2) Lower-level model. On the basis of the upper-level planning, optimize the controllable DG and interruptible load to determine the distribution network operation strategy with the goal of maximizing the annual operating income of the distribution company. The lower model affects the location and capacity of the upper model by returning the time series output value of the controllable unit of the upper model.

2.2. Upper-level optimization model

2.2.1. Objective function. The net present value of the comprehensive income of the power distribution company includes investment cost \( C_I \) and operating income \( C_O \). Operating income is reflected in loss reduction income, emission reduction income, and electricity purchase and sale income after DG access, excluding the DG operation and maintenance cost, and Demand Response (DR) compensation cost. The expression of each part is as follows.

1) Investment cost

\[
C_I = \frac{r(1+r)^n}{(1+r)^n-1} \left( \sum_{i=1}^{N_{WG}} c_{i,WG} P_{i,WG} + \sum_{i=1}^{N_{PV}} c_{i, PV} P_{i, PV} + \sum_{i=1}^{N_{MT}} c_{i, MT} P_{i, MT} \right)
\]  

where \( n \) is the economic service life of DG; \( r \) is the discount rate; \( c_{i,WG}, c_{i, PV} \) and \( c_{i,MT} \) are the investment costs of each type of DG unit capacity; \( P_{i,WG}, P_{i, PV} \) and \( P_{i,MT} \) are the installed
capacity of each type of DG in the \( i \) th node; \( N_{WG}, N_{PV}, \) and \( N_{MT} \) are the access numbers of various types of DG.

(2) Annual operating income

1) DG operation and maintenance cost

\[
C_{OM} = \sum_{s=1}^{S} p_s \left( c_{om,WG} \sum_{i=1}^{N_{WG}} \sum_{t=1}^{H} P_{i,s,t,WG} + c_{om,PV} \sum_{i=1}^{N_{PV}} \sum_{t=1}^{H} P_{i,s,t,PV} + c_{om,MT} \sum_{i=1}^{N_{MT}} \sum_{t=1}^{H} P_{i,s,t,MT} \right)
\]  

(2)

where \( p_s \) is the occurrence probability of scenario \( s \); \( c_{om,WG}, c_{om,PV} \) and \( c_{om,MT} \) are the operation and maintenance costs of each type of DG unit electricity; \( P_{i,s,t,WG}, P_{i,s,t,PV} \) and \( P_{i,s,t,MT} \) are the generation capacity of each type of DG in scenario \( s \) of the \( i \) th node in \( t \) period; \( S \) is the total number of scenarios; \( H \) is the number of intraday periods.

2) Electricity purchase and sale income

\[
C_{CS} = \sum_{s=1}^{S} p_s \left( c_{om,WG} \sum_{i=1}^{N_{WG}} \sum_{t=1}^{H} P_{i,s,t,WG} + c_{om,PV} \sum_{i=1}^{N_{PV}} \sum_{t=1}^{H} P_{i,s,t,PV} + c_{om,MT} \sum_{i=1}^{N_{MT}} \sum_{t=1}^{H} P_{i,s,t,MT} \right)
\]  

(3)

3) Loss reduction

\[
C_{loss} = \sum_{i=1}^{S} \sum_{t=1}^{H} \sum_{l=1}^{N_L} c_{loss} (I_{i,s,t,l}^2 - I_{i,s,t,l}^2) R_l
\]  

(4)

where \( N_L \) is the total number of lines; \( C_{loss} \) is the network loss price; \( I_{i,s,t,l} \) and \( I_{i,s,t,l}^2 \) are the current on the \( l \) th branch in \( t \) period of scenario \( s \) before and after DG connection; \( R_l \) is the resistance of the \( l \)th branch.

4) Emission reduction income

\[
C_{env} = \sum_{s=1}^{S} \sum_{t=1}^{H} \sum_{r=1}^{R} \alpha_{r,G} \beta_r (P_{r,s,t} - P_{r,s,t}^{'})
\]  

(5)

where \( \alpha_{r,G} \) is the emission coefficient of pollutant gas per unit generation of main power grid; \( R \) is the total category of the emitted pollutants; \( \beta_r \) is the treatment cost of different polluting gases; \( P_{r,s,t} \) and \( P_{r,s,t}^{'} \) are the electric power obtained from the power grid before and after DG connection in \( t \) period of scenario \( s \).

5) DR compensation cost

\[
C_{DR} = \sum_{i=1}^{S} \sum_{t=1}^{H} \sum_{r=1}^{R} c_{i,s,t,DR} P_{i,s,t,DR}
\]  

(6)

where \( c_{i,s,t,DR} \) are DR compensation price in \( t \) period of scenario \( s \); \( P_{i,s,t,DR} \) are the DR supply quantity in \( t \) period of scenario \( s \).

In summary, the objective function of the upper-level model is:

\[
\min C = C_T + C_O = C_T + (C_{OM} - C_{CS} - C_{loss} - C_{env} + C_{DR})
\]  

(7)
2.2.2. Constraint condition. The constraints on the number of DG accesses are:

\[
\begin{align*}
    x_{WG,i} &\leq N_{WG}, \forall i \in W_{WG} \\
    x_{PV,i} &\leq N_{PV}, \forall i \in W_{PV} \\
    x_{MT,i} &\leq N_{MT}, \forall i \in W_{MT}
\end{align*}
\]  

(8)

The constraint of the superior power grid is:

\[
P_{G,min} \leq P_{i,s,G} \leq P_{G,max}
\]

(9)

Where \( N_{WG}, N_{PV}, \) and \( N_{MT} \) are the limit of access number of each DG node; \( P_{G,min} \) and \( P_{G,max} \) are the upper and lower limits of interactive power with the upper grid.

2.3. Lower-level optimization model

2.3.1. Objective function. The actual operation strategy of the distribution network is to maximize the total revenue of power distribution companies. Therefore, the lower-level model uses the operating income \( C_o \) in equation (7) as the objective function to optimize the output of the controllable unit and simulate the actual operating conditions.

2.3.2. Constraint condition. 1) Node voltage

\[
U_{\text{min}} \leq U_{i,s,j} \leq U_{\text{max},j}(i \in \Omega)
\]

(10)

where \( U_{\text{max},j} \) and \( U_{\text{min},j} \) are the upper and lower limits of voltage \( U_{i,s,j} \) at node \( i \) respectively; \( \Omega \) is the node-set of distribution network.

2) Load flow equation constraints

\[
\begin{align*}
    P_{i,s,t} &= U_{i,s,t} \sum_{j \in \Omega} U_{j,s,t} (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\
    Q_{i,s,t} &= U_{i,s,t} \sum_{j \in \Omega} U_{j,s,t} (G_{ij} \cos \theta_{ij} - B_{ij} \sin \theta_{ij})
\end{align*}
\]

(11)

where \( P_{i,s,t} \) and \( Q_{i,s,t} \) are the active and reactive power injection of node \( i \) in \( t \) period of scenario \( s \); \( G_{ij} \) and \( B_{ij} \) are the real and imaginary parts of node admittance matrix elements respectively; \( \theta_{ij} \) is the voltage phase angle difference between node \( i \) and node \( j \).

3) Branch capacity constraint

\[
S_{s,i,j} \leq S_{\text{max},ij}
\]

(12)

Where \( S_{\text{max},ij} \) is the extreme value of the transmission power \( S_{s,i,j} \) of the \( i \) th branch.

4) Distributed generation output constraints

\[
\begin{align*}
    P_{i,DG,min} \leq P_{i,DG} \leq P_{i,DG,max} \\
    Q_{i,DG,min} \leq Q_{i,DG} \leq Q_{i,DG,max}
\end{align*}
\]

(13)

Where \( P_{i,DG} \) and \( Q_{i,DG} \) are DG active and reactive power output of node \( i \) respectively; \( P_{i,DG,min} \) and \( P_{i,DG,max} \) are upper and lower limits of DG active output respectively.
3. Model solution

Particle swarm optimization (PSO) is a random optimization algorithm inspired by bird foraging behavior and is based on swarm intelligence [4]. The algorithm is simple in programming, easy to implement, has fewer requirements for objective functions and constraints, and can effectively solve most optimization problems. However, PSO algorithm has the following shortcomings: 1) easy to fall into the local optimal solution; 2) the later period of the algorithm "oscillates" near the global optimal solution, and the convergence becomes slower, which reduces the calculation speed of the algorithm.

In order to improve the convergence speed of the algorithm, this paper uses the method of dynamically adjusting the inertia weight to expand the search space of the particles. The updated equations for the velocity and position of the population particles in the improved PSO (Improved PSO, IPSO) algorithm are as follows.

\[
\begin{align*}
\vec{V}_i^{k+1} &= w \vec{V}_i^k + c_1 r_1 (\vec{P}_i^k - \vec{X}_i^k) + c_2 r_2 (\vec{P}_g^k - \vec{X}_i^k) \\
\vec{X}_i^{k+1} &= \vec{X}_i^k + \vec{V}_i^{k+1} \\
w &= w_{\text{max}} - \frac{w_{\text{max}} - w_{\text{min}}}{T_{\text{max}}} \times k
\end{align*}
\]

Where the label of the particle is \( i = 1,2,K,m \); \( k \) is the iteration algebra; \( \vec{P}_i^k \) is the optimal position of the \( i \) th particle to the \( k \) th iteration; \( \vec{P}_g^k \) is the optimal location of the entire particle swarm by the \( k \) th iteration; \( c_1 \) and \( c_2 \) are learning factors, generally value 2; \( R_1 \) and \( R_2 \) are two random numbers evenly distributed between \([0,1]\); \( w_{\text{max}} \) and \( w_{\text{min}} \) are the maximum and minimum weights respectively; \( \vec{X}_i^k \) is the particle position; \( \vec{V}_i \) is the particle velocity; \( T_{\text{max}} \) is the maximum iteration times.

4. Case study

4.1. Case design

This paper takes the IEEE33-bus power distribution system as an example to simulate the proposed model. The specific parameters of the calculation example can be found in reference [5]. The rated light intensity of PV is 1kW/m². The cut-in wind speed, cut-out wind speed and rated wind speed of WG are 3, 25, and 15m/s respectively. The unit installed capacity of DG is 10kW, and the upper limit of the installed capacity of the access point is 1MW. The unit installed capacity costs of PV, WG and MT are 1200, 900, and 800 USD/kW respectively. The annual variation curve of wind speed, light intensity and load can be found in reference [6]. The particle swarm size of the IPSO algorithm is 100. \( T_{\text{max}} \) is 200. Both \( c_1 \) and \( c_2 \) are taken as 2. \( w_{\text{max}} = 0.9 \), \( w_{\text{min}} = 0.4 \).

4.2. Results

The planning results obtained by using the method proposed in this paper and the corresponding operating income of power distribution companies are shown in Table 1 and Table 2 respectively.

| Configuration object | Optimized configuration results       | Total capacity/kW |
|----------------------|--------------------------------------|-------------------|
| WG                   | bus-4,bus-7,bus-25,bus-29            | 1200              |
| PV                   | bus-4,bus-14,bus-25                  | 600               |
| MT                   | bus-29                               | 500               |

Table 1. Planning results.
Table 2. Various economic indicators of the planning results.

| Indicator type                                    | Calculated value/Million US dollars |
|-------------------------------------------------|------------------------------------|
| Investment cost                                 | 23.43                              |
| Income from electricity purchase and sale       | 60.84                              |
| Reduce environmental pollution benefits         | 39.82                              |

It can be seen from Table 1 that since the installation cost of WG is less than that of PV, WG access is preferred in the decision-making process. As can be seen from Table 2, although the power distribution company has more costs in terms of DG investment, operation and maintenance, and DR compensation, it has gained benefits in purchasing and selling electricity, delaying line upgrading, improving power supply reliability, reducing losses and reducing environmental pollution. The total income obtained by a comprehensive calculation is 523,200 US dollars.

The planning method proposed in this paper is based on the operation strategy formulated by the power distribution company, and the decision is made with economy as the optimization goal. Therefore, it is necessary to conduct a sensitivity analysis of price factors. Considering that both DG sales price contract and DR compensation price contract signed by distribution companies and customers have negotiation process, the two price factors are uncertain. In order to explore the impact of the DG sale price and DR compensation price signed by the distribution company and the user on the planning result, the following five schemes are designed. The DR compensation price is the same in schemes 1 to 3, and the DG sale price are 0.8, 0.7, and 0.6 times the time-of-use price respectively. Schemes 2, 4, and 5 have the same DG sale price. Scheme 4 does not consider DR. The DR compensation prices in schemes 2 and 5 are 0.07 USD/(kW·h) and 0.04 USD/(kW·h) respectively. The planning results of the 5 schemes are shown in Figure 2.

Comparing the planning results of schemes 1 to 3 in Table 3, it can be seen that with the decrease of the DG sales price, the DG investment cost decreases correspondingly, while the DR compensation cost increases. Combined with the operating income, it can be seen that DG access capacity is positively correlated with DG sales price. When the DG sales price is lower, the more DG is invested, the worse the economy will be. Therefore, the optimization model chooses to invest more in DR instead of DG. Comparing the planning results of schemes 2 and 5 in Table 3, it can be seen that when the DR compensation price increases, the corresponding DR compensation cost decreases, while the DG
investment cost increases accordingly. When the DR compensation price is higher, investing in DG is more economical than investing in DR. Comparing the planning results of scheme 2 and 4, it can be seen that the DG investment cost of scheme 4 is less than that of scheme 2. This is because DR has the function of smoothing the equivalent load curve and can improve the system's ability to accept renewable energy.

5. Conclusion
Aiming at the distributed generation (DG) programming problem of power companies that have distribution network assets and operating rights in a market environment, this paper proposes a DG bi-level optimization model considering the interests of distribution companies. The following conclusions are obtained through the simulation results of examples. Under the planning background of considering the operation income of power distribution company, the price of DG sales and DR compensation price can effectively guide the optimal allocation of DG and further improve the comprehensive income of power distribution company.

If the DG sales price is too low, it will affect the economic benefits of investment in DG. If DR is chosen to invest instead of controllable DG, the economy will be higher. DR can effectively improve the system's ability to accept renewable energy, and the DR compensation price will affect the economy of planning results. If the DR compensation price is unreasonable, the investment benefit may be lower than that without considering DR.

Acknowledgments
The paper is supported by The Science and Technology Project of SGCC, (Research on the competition situation and operation mode of distribution companies in the park 52170018000S).

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