The distribution network planning considering distributed power supply and battery energy storage station

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1. Introduction

Distributed generation (DG) has developed rapidly in recent years, which can not only realize the effective use of renewable energy, but also adjust the peak-valley difference and can improve the reliability and flexibility of power system, in this way DG can be the development direction of electric power industry in the 21st century[1,2]. However, due to the intermittence and randomness of renewable energy power generation in DG, it is necessary to build energy storage devices to ensure the smooth utilization of distributed power [3]. Traditional distribution network planning method is to reasonably design expanded grid structure and capacity according to the load forecasting results of local as well as the built power grid structure in a certain planning period, which aims to meet the demand of load growth and the safety of power grid conditions and make the distribution network construction and the running economy to achieve the optimal goal [4]. The access of distributed power generation and energy storage equipment changes the type of source load that are not considered in the traditional planning of distribution network [5].

At present, there are many literatures about the mathematical model of distribution network planning, many of which have introduced the planning problems of distribution network with the connection of distributed power supply and energy storage equipment. An improved multi-objective hybrid quantum genetic algorithm based on the distributed power planning method is established in [6], which can make the processing results of distributed power distribution network planning more rationality and feasibility. The improved multi-population genetic algorithm proposed in [7] is applied to the multi-objective distribution network planning problem, which provides a specific repair scheme for the infeasible solution generated under the genetic operation. In [8], a distribution network planning mathematical model with comprehensive consideration of substation planning and feeder planning is proposed and established, which has good results for global optimization of distribution network comprehensive planning.
However, most of the researches only considered the distributed generation or storage device individual interconnection of power distribution network planning problem, and most of them only focused the distribution network planning with one year planning period. This paper constructs a comprehensive distribution network planning model with the consideration of the new substation, new lines, distributed generation and energy storage device interconnection together and extends the fixed number of the planning period in the model. Besides, by considering the distribution network construction and the time value of operation maintenance cost, the goal of distributed generation and energy storage equipment access of the medium and long-term planning can be achieved, and the results of the research will provide decision support for the regional long-term distribution network planning.

2. Model construction

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2.1. Objective function

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\[
\text{Min } F = F_{CO} + F_{PD} - F_{C}
\]

Where FCO represents the investment expenses of the distribution network construction and upgrading; FPD represents the cost of distribution network operation; FC represents government subsidies for renewable energy generation.

2.2. FCO: Investment expenses of distribution network construction and upgrading

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

Where \( F_{SS} \) represents investment expenses of new substation; \( F_{FD} \) represents investment expenses of new lines; \( F_{DG} \) represents investment expenses of new DGs; \( F_{RES} \) represents investment expenses of new DGs using renewable energy; \( F_{BES} \) represents investment expenses of new battery storage station.

In this paper, the total investment costs of various components can be divided into two categories according to whether the investment costs are associated with design capacity. Taking FSS for example, the mathematical expressions can be expressed as shown below:

\[
F_{SS} = \sum_{i=1}^{T} C_i \sum_{i \in \text{DGs}} \left( P_{i,j}^{SS} \sigma_{i,j} + Q_{i,j}^{SS} M_{i,j}^{SS} \right)
\]

Where,

\[
C_i = \frac{1}{(1+u)^{i-1}}
\]

\[
P_{i,j}^{SS} = F_i (1 + s)^j \left( \frac{i(1+i)^k}{((1+i)^k - 1)} + T \sum_{l=0}^{ek} \frac{1}{(1+u)^{e_l}} \right)
\]
\[ Q_{i,t}^{SS} = \left\{ E_i(1+s)^{t-1} \left( \frac{i(1+i)^{t_i}}{(1+i)^{t_i} - 1} + T_i \right) + O_i \right\} \frac{PH}{(1+u)^{t-1}} + 8760c_i^{SS} \sum_{t=1}^{PH} \epsilon_i^{SS,AVG} \]  

where \( u \) represents internal rate of return; \( C_t \) represents present value coefficient of the year \( t \) discount to the start of the planning period; \( F_i \) represents total amount of capital not related to substation construction capacity for initial investment; \( T_i \) represents tax rate related; \( i \) represents average interest rate during the service life of a substation; \( S \) represents the annual growth rate of construction investment costs; \( P_i^{SS} \) represents the present value coefficient of capital in year \( t \) discounted at the investment cost at node \( i \) independent of the capacity of the substation; \( E_i \) represents equipment and construction costs related to capacity of new substations($/MVA); \( O_i \) represents the operating expenses of substations($/MVA); \( c_i^{SS} \) represents hysteresis loss coefficient(MV/MVA); \( \epsilon_i^{SS,AVG} \) represents electricity loss cost of substation ($/MVA); \( \Omega_{SS} \) represents the indicator set of the substation nodes.

2.3. FPD: Cost of distribution network operation
In this paper, when calculating the operating cost of distribution network, the purchasing cost of substation and the reduced generation cost of power generation using renewable energy are mainly considered. The calculation formula is as follows:

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

Where \( P_{SSE} \) represents electricity purchasing cost of substations; \( P_{SSD} \) represents the extra charge that a power company needs to pay to the generator during peak hours; \( P_{RES} \) represents reduced electricity purchasing costs of DGs for using renewable energy; \( P_{DG} \) represents electricity purchasing costs of DGs for using traditional energy.

2.4. Electricity purchasing costs

\[ P_{SSE} = 26280 pf \sum_{i=1}^{T} \sum_{t=1}^{PH} C_i \left\{ \gamma f_{i,t}^{OFF} \epsilon_i^{SS,OFF} S_{i,t}^{SS,OFF} + (1-\gamma) f_{i,t}^{ON} \epsilon_i^{SS,ON} S_{i,t}^{SS,ON} \right\} \]

\[ P_{RES} = -8760 \sum_{i=1}^{T} \sum_{t=1}^{PH} \epsilon_{i,t}^{AVG} r_i^{RG} M_{i,t}^{RG} \]

\[ P_{DG} = 26280 pf \sum_{i=1}^{T} \sum_{t=1}^{PH} C_i \sum_{k=1}^{PH} \epsilon_{i,t}^{DG} \left\{ \gamma f_{i,t}^{OFF} S_{i,t}^{DG,OFF} + (1-\gamma) f_{i,t}^{ON} S_{i,t}^{DG,ON} \right\} \]  

Where \( pf \) represents average power coefficient of the power grid; \( C_i \) represents the present value coefficient of capital discount from year \( t \) to the beginning of the planning period; \( \gamma \) represents the proportion of electricity consumption for the valley time of the total electricity consumption; \( f_{i,t}^{OFF} \) and \( f_{i,t}^{ON} \) respectively represent the load coefficients at the bottom and peak periods of power grid in year \( t \); \( \epsilon_i^{SS,OFF} \) and \( \epsilon_i^{SS,ON} \) respectively represent the purchase price of substation \( i \) in the valley and peak hours.
of year t($/MWh); \( S_{i,t}^{SSH,OFF} \) and \( S_{i,t}^{SSH,ON} \) respectively represent the high voltage power capacity of substation i in the valley and peak hours of year t(MVA); \( P_{SS} \) represent the present value of costs of substation electricity purchase is discounted to capital at the beginning of the planning period; \( \Omega_{SS} \) represents the indicator set of the substation nodes; \( r_{BG} \) is the capacity coefficient of DGs using renewable energy, which is the ratio of the average generating capacity of the power source to the designed installed capacity; \( e_{i,t}^{AVG} \) represents electricity purchasing costs at node i in year t; \( M_{r,i}^{BG} \) represents the installed capacity of renewable energy DGs at node i in year t(MVA); \( P_{RES} \) represents reduced electricity purchasing cost for using renewable energy.

2.5. Electricity purchasing costs

Represents reduced electricity purchasing cost for using renewable energy

The government subsidies for renewable energy power generation in this paper is that the government issued relevant policies and standards to provide certificates for renewable energy generation under the electricity market environment, which has gradually matured in the European and American power markets. The development of renewable energy has played a good incentive and guiding role. Referring to the relevant foreign standards, the specific calculation formula is as follows:

\[
F_c = 8760 \sum_{i=1}^{n} c_i \sum_{s \in \Omega_{SS}} q_{s,i}^{RE} r_{BG} \sum_{r \in \Omega_{SS}} M_{r,i}^{BG}
\]

Where, \( q \) represents the market price of a unit certificate; \( r \) represents capacity coefficient of renewable energy generation; \( M \) represents installed capacity for using renewable energy sources;

2.6. Constraints

(1) Kirchhoff’s conservation law constraint.

For built substations in the distribution network:

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

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

Where, \( S_{i,t}^{SSH,ON} \) and \( S_{i,t}^{SSH,OFF} \) respectively represent the high voltage power capacity of substation i in the peak and valley hours of year t(MVA/phase); \( Z_{i,t}^{SS} \) represents the impedance of substation i(ohm); \( V \) represents the average voltage amplitude in the grid(kV); \( S_{i,t}^{SS,ON} \) and \( S_{i,t}^{SS,OFF} \) respectively represent the output capacity of substation i in the peak and valley hours of year t(MVA/phase).

For all nodes in the grid:

\[
\sum_{i \in \Omega_{SS}} (S_{i,t}^{ON} + Z_{i,t}^{FR} (S_{i,t}^{ON})^2) + S_{i,t}^{SS,ON} + S_{i,t}^{DG,ON} = S_{i,t}^{ON}
\]

\[
\sum_{i \in \Omega_{SS}} S_{i,t}^{OFF} = \sum_{i \in \Omega_{SS}} (S_{i,t}^{OFF} Z_{i,t}^{OFF} (S_{i,t}^{OFF})^2) + S_{i,t}^{SS,OFF} + S_{i,t}^{DG,OFF} = S_{i,t}^{OFF}
\]

Where, \( S_{i,t}^{ON} \) represents the apparent power value of node j entering node i through line ij in the peak and hours of year t (MVA/phase); \( Z_{i,t}^{FR} \) represents the impedance of line ij(ohm); \( S_{i,t}^{SS,ON} \) and \( S_{i,t}^{SS,OFF} \) respectively represent the power capacity output from substation i and DG i in the peak and hours of year t (MVA/phase); \( S_{i,t}^{ON} \) represents the power demand of node i in year t, (MVA/phase).

(2) Capacity constraint
\[0 \leq M_{ij}^{SS} \leq U_i^{SS} \sigma_{ij}^{SS}\]
\[0 \leq M_{ij}^{DG} \leq U_i^{DG} \sigma_{ij}^{DG}\]
\[0 \leq M_{ij}^{BG} \leq U_i^{BG} \sigma_{ij}^{BG}\]
\[0 \leq M_{ij}^{FR} \leq U_{ij}^{FR} \sigma_{ij}^{FR}\]
\[0 \leq M_{ij}^{RS} \leq U_i^{RS} \sigma_{ij}^{FR}\]
\[S_{ij}^{ON} \leq \frac{1}{3} U_i^{SS}\]
\[S_{ij}^{ON} + S_{ji}^{ON} \leq \frac{1}{3} U_{ij}^{FR}\]

Where \(M\) represents three-phase capacity of components in a distribution network; \(U\) represents max three-phase capacity allowed to be installed at the node; \(\sigma\) is a decision variable.

(3) Node voltage constraint
For built lines in the distribution network:
\[V_{ij} = V_i + \frac{(S_{ij}^{ON} - S_{ji}^{ON})}{V_i} Z_{ij}\]  
(13)

Where \(V_{ij}\) represents phase voltage at node \(i\) in year \(t\) (kV); \(V_i\) represents average voltage amplitude in year \(t\).

For new lines in the distribution network:
\[V_{ij} \leq V_{ij} + \frac{(S_{ij}^{ON} - S_{ji}^{ON})}{V_i} Z_{ij} + G \left[1 - \sum_{t \in \Omega} \sigma_{ij}^{FR}\right]\]
\[V_{ij} \geq V_{ij} + \frac{(S_{ij}^{ON} - S_{ji}^{ON})}{V_i} Z_{ij} - G \left[1 - \sum_{t \in \Omega} \sigma_{ij}^{FR}\right]\]  
(14)

Where, \(G\) is a control variable; \(\sigma^{FR}\) is a 0-1 decision variable of building new transmission lines.

For all nodes in the distribution network:
\[V_{\text{min}} \leq V_{ij} \leq V_{\text{max}}\]  
(15)

Where \(V_{ij}\) is the phase voltage amplitude of node \(i\) in year \(t\) (KV); \(V_{\text{min}}\) and \(V_{\text{max}}\) are the minimum and max allowable phase voltage in the grid(KV).

(4) Grid security constraint
For power generation safety constraints:
\[\sum_{ij \in \Omega^{DG}} M_{ij}^{SS} + \sum_{ij \in \Omega^{ON}} M_{ij}^{SS} + \sum_{ij \in \Omega^{DG}} M_{ij}^{DG} \geq 3 \mu_{\text{gen}} \sum_{k \in \Omega^{ON}} S_{k,j}^{ON}\]  
(16)

Where, \(M_{ij}^{SS}\) represents installed capacity of built substations; \(M_{ij}^{SS}\) represents installed capacity of new substations; \(M_{ij}^{DG}\) represents installed capacity of new DGs; \(S_{k,j}^{ON}\) represents the demand capacity of node \(k\) during peak hours (MVA/phase); \(\mu_{\text{gen}}\) is the safety factor of generation which is usually between 1.2 and 1.3.

For transmission lines safety constraints:
\[ m_{j,0} + \sum_{i=1}^{T} \sum_{t=1}^T \sigma_{g,ij,t}^{FR} \geq m_{j,t} \]  

(17)

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

(5) Battery storage station balance constraints

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

(18)

Where, \( \gamma \) represents the proportion of electricity consumption for the valley time of the total electricity consumption; \( \eta_i \) represents storage efficiency of battery storage stations;

(6) Other constraints

This set of constraints is to ensure that there is at most one new substation, one distributed power source, and one new circuit between one node or two nodes during the planning period.

\[ \sum_{i=1}^{T} \sigma_{i,SS} \leq 1, \forall i \in \Omega_{SSnew} \]

\[ \sum_{i=1}^{T} \sigma_{ij,FR} \leq 1, \forall ij \in \Omega_{FRnew} \]

\[ \sum_{i=1}^{T} \sigma_{ij,DG} \leq 1, \forall i \in \Omega_{DGnew} \]  

(19)

\[ \sum_{i=1}^{T} \sigma_{ij,RG} \leq 1, \forall i \in \Omega_{RGnew} \]

\[ \sum_{i=1}^{T} \sigma_{ij,BS} \leq 1, \forall i \in \Omega_{BSnew} \]

where \( \sigma \) is a binary decision variable; \( \Omega_{SSnew} \), \( \Omega_{FRnew} \), \( \Omega_{DGnew} \), \( \Omega_{RGnew} \) and \( \Omega_{BSnew} \) respectively represent node indicator set of new substations, new transmission lines, new distributed power sources, new renewable energy power generation and new battery energy storage stations.

3. Case and results analysis

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References are cited in the text just by square brackets [1]. Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under heading references, see our example below.

The case is that in the initial network there are 11 nodes and 9 transmission line of 25kV. The aim is to expand to a network including 16 nodes and 16 transmission lines with DGs and renewable energy generation. The initial network frame structure is shown in figure 1:
Figure 1. Initial network structure.

Assume that the extension planning life of distribution network is 5 years; the load growth rate of each load node is 4%. The service life of substations and transmission lines is 30 years. The service life of distributed power is 15 years. The life of a renewable power source is 10 years. The market price of a renewable energy certificate is 700 yuan/MWh. The max voltage allowed by the load node is 5%. The max load of substations and transmission lines shall not exceed 10% of their rated capacity; the average annual increase in energy prices is 5%. Construction and equipment costs increase by 7% annually; the internal rate of return is 10%. The tax rate is 3%. The bank rate is 8% a year.

The technical parameters and construction costs of each component in the distribution network are shown in table 1-12:

| Substation number/ node number | Rated capacity of transformer (MVA/ three phase) | Current max load (MVA/ three-phase) | Impedance (%) | Iron loss (MW/MVA) |
|-------------------------------|-----------------------------------------------|-----------------------------------|---------------|-------------------|
| SS1/1                         | 2*23                                          | 39.696                            | 6.15          | 0.0354            |
| SS2/2                         | 4*3                                           | 6.966                             | 5.0           | 0.0305            |

Table 2. Power purchasing cost of built substation

| Substation | Peak time price (yuan/MWh) | Average peak valley price ratio |
|------------|----------------------------|--------------------------------|
| SS 1       | 349.32                     | 0.665                          |
| SS 2       | 282.9                      | 0.600                          |
Table 3. Load node parameters

| Load node number/node number | Demand in peak time (MVA/phase) | Ratio of valley-peak time | Peak load factor | Valley load factor | Power factor |
|-----------------------------|--------------------------------|---------------------------|-----------------|-------------------|-------------|
| DL1/3                       | 1.950                          | 0.623                     | 0.448           | 0.666             | 0.912       |
| DL2/4                       | 2.487                          | 0.613                     | 0.376           | 0.751             | 0.867       |
| DL3/5                       | 2.802                          | 0.534                     | 0.622           | 0.622             | 0.955       |
| DL4/6                       | 2.828                          | 0.569                     | 0.348           | 0.421             | 0.926       |
| DL5/7                       | 1.591                          | 0.548                     | 0.476           | 0.750             | 0.885       |
| DL6/8                       | 1.574                          | 0.729                     | 0.487           | 0.694             | 0.926       |
| DL7/9                       | 1.821                          | 0.675                     | 0.611           | 0.611             | 0.949       |
| DL8/10                      | 0.343                          | 0.607                     | 0.484           | 0.661             | 0.944       |
| DL9/11                      | 0.158                          | 0.688                     | 0.390           | 0.730             | 0.909       |

Table 4. Operating parameters and cost of planned substation

| Substation number/node number | Fixed initial investment cost(yuan) | Equipment and installation costs (yuan/MVA) | Tax rate (%/year) | Annual operating and maintenance costs(yuan/MVA) | Transformer capacity allowed(MVA/three phase) | Transformer impedance (%) | Iron loss (MW/MVA) |
|-------------------------------|-------------------------------------|---------------------------------------------|-------------------|-------------------------------------------------|-----------------------------------------------|--------------------------|-------------------|
| SS3/12                       | 4,215, 210                          | 222,882                                     | 3                 | 31,543                                          | 20                                            | 5                        | 0.03              |
| SS4/13                       | 6,055, 905                          | 180,576                                     | 3                 | 36,217                                          | 20                                            | 5                        | 0.03              |

Table 5. Power purchasing cost of planned substation

| Substation | Peak time price(yuan/MWh) | Average peak valley price ratio |
|------------|---------------------------|---------------------------------|
| SS 3       | 319.185                   | 0.630                           |
| SS 4       | 322.875                   | 0.674                           |

Table 6. Potential Load node parameters

| Load node number/node number | Demand in peak time (MVA/phase) | Ratio of valley-peak time | Peak load factor | Valley load factor | Power factor |
|-----------------------------|--------------------------------|---------------------------|-----------------|-------------------|-------------|
| DL10/14                     | 0.317                          | 0.480                     | 0.449           | 0.763             | 0.90        |
| DL11/15                     | 0.560                          | 0.536                     | 0.392           | 0.666             | 0.95        |
| DL12/16                     | 0.077                          | 0.600                     | 0.543           | 0.923             | 0.88        |

Table 7. Parameters of built transmission lines

| Line Number | Line length(km) | Current max load (MVA/phase) | Max capacity (MVA/three-phase) | Resistance (ohm/km) | Reactance (ohm/km) |
|-------------|-----------------|-------------------------------|-------------------------------|---------------------|--------------------|
| FR1         | 5.8400          | 1.574                         | 2.70                          | 3.689               | 0.543              |
| FR2         | 3.8045          | 2.487                         | 3.50                          | 1.594               | 0.519              |
| FR3         | 2.6104          | 5.316                         | 5.75                          | 0.481               | 0.443              |
| FR4         | 1.1885          | 2.802                         | 3.90                          | 0.963               | 0.469              |
| FR5         | 2.0008          | 3.541                         | 3.90                          | 0.963               | 0.469              |
| FR6         | 3.5189          | 1.591                         | 2.00                          | 3.689               | 0.543              |
| FR7         | 3.3779          | 0.344                         | 1.5                           | 5.859               | 0.561              |
| FR8         | 2.1626          | 0.518                         | 1.5                           | 5.859               | 0.561              |
| FR9         | 1.8472          | 1.821                         | 3.50                          | 1.594               | 0.519              |
### Table 8. Construction costs of planned transmission lines

| Line Number | Fixed initial investment cost(yuan/km) | Equipment and installation costs(yuan/MVA-km) | Tax Rate(%/year) | Annual operating and maintenance costs(yuan/km) |
|-------------|----------------------------------------|-----------------------------------------------|------------------|-----------------------------------------------|
| FR10        | 57,760                                 | 4,473                                         | 3                | 2,521.7                                       |
| FR11        | 49,919                                 | 5,939                                         | 3                | 2,089.2                                       |
| FR12        | 69,330                                 | 5,462                                         | 3                | 3,442.5                                       |
| FR13        | 56,584                                 | 6,304                                         | 3                | 2,248.6                                       |
| FR14        | 53,766                                 | 3,944                                         | 3                | 3,133.8                                       |
| FR15        | 42,866                                 | 4,966                                         | 3                | 2,426.3                                       |
| FR16        | 74,826                                 | 5,639                                         | 3                | 3,464.9                                       |

### Table 9. Initial parameters of planned transmission lines

| Line Number | Line length(km) | Max installed capacity allowed (MVA/ three-phase) | Resistance (ohm/km) | Reactance(ohm/km) |
|-------------|-----------------|-----------------------------------------------|---------------------|-------------------|
| FR10        | 6.6790          | 10                                           | 2.743               | 0.514             |
| FR11        | 5.0966          | 10                                           | 2.743               | 0.514             |
| FR12        | 3.8707          | 10                                           | 2.743               | 0.514             |
| FR13        | 1.5022          | 10                                           | 2.743               | 0.514             |
| FR14        | 1.8474          | 10                                           | 2.743               | 0.514             |
| FR15        | 4.4163          | 10                                           | 2.743               | 0.514             |
| FR16        | 5.6113          | 10                                           | 2.743               | 0.514             |

### Table 10. Costs of planned DGs using traditional energy

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

### Table 11. Costs of planned DGs using renewable energy

| DG number/ node number | Fixed initial investment cost(yuan) | Equipment and installation costs(yuan/MVA) | Tax rate(%/year) | Annual operating and maintenance costs(yuan/MVA) | Max installation capacity(MVA/ three-phase) | Capacity factor |
|------------------------|-------------------------------------|--------------------------------------------|------------------|-----------------------------------------------|---------------------------------------------|-----------------|
| RG1/7                  | 677,435                             | 7,622,439                                  | 0                | 27,503                                        | 0.5                                         | 0.567           |

### Table 12. Parameters and costs of planned battery storage station

| Battery storage station number/ node number | Fixed initial investment cost(yuan) | Equipment and installation costs(yuan/MVA) | Tax rate(%/year) | Annual operating and maintenance costs(yuan/MVA) | Max installation capacity(MVA/ three-phase) | Energy storage efficiency(%) |
|--------------------------------------------|-------------------------------------|--------------------------------------------|------------------|-----------------------------------------------|---------------------------------------------|-----------------------------|
| BS1/7                                     | 528,568                             | 2,637,710                                  | 3                | 58,425                                        | 25                                          | 78                         |
According to the parameters and the load of each node, after linearization of constraint condition, the traditional genetic algorithm (GA) with the tool of Matlab is used to simulate the example. It is concluded that the distribution network extended decision shown in the following table:

### Table 13. Distribution network extended decision

| Decision variables | Designed installed capacity (three-phase) |
|--------------------|------------------------------------------|
| \( M_{1,1}^{\text{RG}} \) | 0.5MVA |
| \( M_{3,1}^{\text{BS}} \) | 21MWh |
| \( M_{10,1}^{\text{FRN}} \) | 6MVA |
| \( M_{3,2}^{\text{SS}} \) | 6.5MVA |
| \( M_{11,2}^{\text{FRN}} \) | 4.5MVA |
| \( M_{12,2}^{\text{FRN}} \) | 4, 5MVA |
| \( M_{13,2}^{\text{FRN}} \) | 1.875MVA |
| \( M_{14,2}^{\text{FRN}} \) | 1, 875MVA |
| \( M_{15,2}^{\text{FRN}} \) | 1.875MVA |

Where \( M_{ij}^{XX} \) represents the capacity of components (MVA/three-phase); \( XX \) is the type of element that the variable represents; \( i \) is the number in the category element; \( t \) represents construction time. At the end of the planning life, the network structure is shown in figure 2 and the cost of each item in the final objective function is shown in table 14.

![Figure 2. Final network structure](image-url)
Table 14. Construction cost in the objective function

| Item                                           | Cost(yuan)     |
|------------------------------------------------|----------------|
| $F_{ss}$ New substation                        | 5,350,746      |
| $F_{fn}$ New lines                             | 976,725        |
| $F_{res}$ Renewable energy DG                  | 2,386,736      |
| $F_{bas}$ New battery storage station          | 70,513,200     |
| $P_{e}$ Electricity purchasing cost of substation | 218,706,841   |
| $P_{res}$ Reduced electricity purchasing cost for using renewable energy | 3,062,651 |
| $F_{s}$ Subsidies for renewable energy generation | 6,368,651     |
| **Total**                                      | **288,962,946**|

4. Conclusion

This paper constructed a PDEP programming model which considers DG, especially renewable energy as an energy distributed power supply and battery energy storage station connecting to the power distribution network. The Model takes the capital cost present value of distribution network construction and expansion as the objective function and meets the requirements of load growth and power grid safe operation indicators, and will support to establish a comprehensive distribution network planning decision support system.

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