Research on Multi-Scenario Distributed Wind and Photovoltaic Power Accommodation Capacity of Distribution Network Based on Time Series Production Simulation

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Abstract. With the large-scale access of distributed new energy into the distribution network, the evaluation on the accommodation capacity of distributed new energy in the distribution network has important guiding significance for the scientific planning of distributed generation and grid connection. Considering the parked and regionalized development trend of distributed power generation mode, this paper proposes a method for evaluating the distributed wind and photovoltaic power accommodation capacity of regional distribution networks based on time series production simulation from the perspective of practical applications. Based on the timing difference and complementarity of the load characteristics of substations on the distribution network side, we conducted an evaluation on the distributed wind and photovoltaic power accommodation capacity of the regional distribution network, and through taking the flexible operation mode of the distribution network side into consideration, realized the mutual assistance from time domain and space dimension of distributed new energy consumption and carrying capacity of various substations. Through establishing a mathematical model for the consumption and carrying capacity analysis in the multi-scenario modes such as local node consumption, local station consumption and allowing certain percentage of abandoned electricity, we came out the scale of the maximum consumption of distributed new energy in different scenarios as well as the overall grid connection layout scheme. In the end, we used such evaluation method to conduct an empirical analysis on the distribution network in certain region, verified the correctness and effectiveness of the model, and provided theoretical supports for guiding the regional distributed new energy overall planning and scientific grid connection.

1. Introduction
In recent years, the state has issued a number of policies concerning the distributed power generation, to encourage and promote the development of distributed photovoltaic power generation. According to the statistical data, as of 2018, the cumulative installed capacity of distributed photovoltaic power in China reached 50.61GW, with a year-on-year growth of 70.6% compared with that of 2017. Therefore, the power grid is facing huge challenges brought about by large-scale, clustered distributed generation and grid connection [1], and the evaluation on the power grid's consumption capacity of distributed new energy would be of great significance.

Scholars at home and abroad have conducted researches on the consumption capacity of distributed new energy from different perspectives. In terms of planning and design, they conducted researches on improving the consumption capacity of distributed power sources through focusing on two aspects of the total planned capacity of distributed power sources [2-9] and the reconstruction of distribution networks [10-13]. In terms of dispatch control optimization, they put forward the control strategy to improve the consumption capacity of distributed new energy through flexible coordination of power sources, active power distribution networks and other network source coordination measures; in terms
of grid-connection equipment, they carried out analysis on converters, measurement and control protection technologies, and proposed the research methods for improving the consumption capacity of distributed new energy [1]. Reference 2 used the busbar voltage and short-circuit current as constraints to comprehensively conclude the calculation method and evaluation strategy for the target value range of access capacity, which lacked the analysis on the interactive influence of multiple distributed photovoltaic power sources on the voltages of each node in the distribution network. References [8], [14] and [15] all established models with the objective of economical optimization to solve the power grid's maximum consumption of distributed power sources, and failed to form a specific distributed power grid connection scheme; References [16-18] all added distributed power sources at the specific node of the regional distribution network as boundary conditions, to obtain the maximum consumption capacity of a certain local site, thus failed to achieve the overall planning objective; References 19 and 20 both used the time series production simulation methods to study on the site selection and capacity determination and optimization of distributed wind and photovoltaic power accommodation capacity of regional distribution network, however, these studies failed to consider the actual access conditions of projects and the topology structure of distribution networks. The above researches on distributed new energy planning mostly focused on the local stations of distribution network, operating economics, overall planned installed capacity levels and other aspects, but lacked the overall planning researches which take into account the entire network structure, load characteristics, operating methods, reasonable access points and other aspects. From the perspective of practical applications, this paper mainly considered access conditions, load characteristics and other factors at the local site level of the power grid, and mainly considered grid network topology structure, energy flow distribution and other factors at the overall grid level, then used the time series production simulation method to build multi-scenario distributed new energy consumption mathematical model, which effectively realized the multi-dimensional mutual assistance between various nodes in the aspects of access conditions and consumption space, and obtained the comprehensive distributed new energy site selection and capacity determination plan for the regional power grid with overall planning and operability.

2. Method Analysis
Distributed new energy is mostly integrated into the low and medium voltage power grids at voltage levels of 110kV and below [1], and most substations in the low and medium power grids are directly connected to the power load. Due to the different types of users, it often has the characteristic of large load differences between sites, based on which if we conduct analysis on the overall load consumption space of the regional power grid, there may be cases where the load characteristics of some sites extremely mismatches the output characteristics of the distributed new energy access by them, or the consumption volume of distributed new energy obtained by some extreme scenarios which underutilize the consumption space of regional grid.
In order to make a comprehensive planning for the mutual assistance between each node in the regional power grid and make full use of the regional grid's consumption space of distributed new energy, we worked out a comprehensive distributed new energy grid-connected planning scheme with strong perform-ability. This paper introduced the time series production simulation method, to conduct the production simulation of the dynamic distribution of energy flow in certain time step in the regional distribution network; in the meantime, through taking into account the sensitivity analysis needs of distributed new energy consumption in different scopes, established the consumption capacity calculation model for the regional distribution network with multi-scenario planning, thus provided effective supports for the long-term development of regional distributed new energy.

2.1. Time Series Production Simulation Method
Time series production simulation could simulate the operation of hour-level power systems, and dynamically simulate various operating conditions for the load and distributed new energy output fitting, thus to provide supports for scheduling operation optimization, industrial development planning, grid construction planning and other aspects. Due to the relative complexity of network topology structure of the regional power distribution network and the diversity of access conditions,
load levels and characteristics of each node, this paper fully considered the constraint conditions such as access conditions, load levels and characteristics of each node in the distribution network, as well as network topology structure in the simulation process, and dynamically simulated the energy flow distribution of the distribution network after connecting distributed new energy, and proposed a distributed new energy grid-connected scheme with the objective of maximizing consumption capacity.

2.2. Multi-Scenario Calculation Method for the Accommodation Capacity of Distributed New Energy by the Distribution Network
 Considering that after the distributed new energy has been connected into power grid, there would be various scenarios such as complete consumption by the local station, complete consumption by the station area, excess power delivery after consumption by the station area, and the consumption with a certain proportion of abandoned electricity, this paper carried out the analysis on the accommodation capacity of distributed new energy by the regional distribution network.

2.2.1 Scenario 1
 Scenario 1 is the local consumption model, where the power generated by distributed new energy connected to each node of the regional power grid is consumed at its access node, so as to avoid counter flows.

2.2.2 Scenario 2
 Scenario 2 is the consumption model within the scope of the regional power grid, where the power generated by the distributed new energy after it has been connected into each node could be transmitted upward on the basis of satisfying the constraint conditions, but it is only consumed locally within the scope of the regional power grid. This scenario enables the effective use of the mutual assistance of access resources and consumption space between nodes, so as to maximize the consumption of distributed new energy.

2.2.3. Scenario 3
 In order to effectively compensate for the uneven distribution of the consumption space among different regional power grids, scenario 3 allows regional power grids to transmit certain amount of power on the basis of scenario 2, so as to maximize the consumption of distributed new energy at the level of the entire regional distribution network.

2.2.4. Scenario 4
 Due to the mismatch between the load characteristics and the output characteristics of distributed new energy, power abandonment often occurs in low load periods and peak time of distributed new energy generation, with a short power abandonment period. If a small amount of power abandonment is allowed, it could greatly improve the power grid's accommodation capacity of distributed new energy. Therefore, scenario 4 allows a certain proportion of power of distributed new energy based on scenario 3.

3. Mathematical Model

3.1. Objective Function
 Through putting the substations at 110kV/220kV voltage level as the main node, we divided the regional power grid into relatively independent multiple regional power grids, and conducted analysis on each regional power grid. Taking the maximum distributed wind power and photovoltaic installed capacity that could be connected into the regional power grid as the objective function, the corresponding calculation is detailed in equation 1:

$$\max \sum (G_{aw} + G_{ap})$$
where \( G_{w,n} \) refers to the distributed wind power installed capacity connected into the \( n \)th node, and \( G_{pv,n} \) refers to the distributed photovoltaic installed capacity connected into the \( n \)th node.

### 3.2. Constraint Conditions

#### a. Network Congestion Constraints

\[
\max_{0 < t < T} (S_{mL}) \leq S_{mL,max}
\]

where, \( S_{mL} \) refers to the maximum energy flow on the \( m \)th network branch, and \( S_{mL,max} \) refers to the delivery and transformation capacity of this branch.

#### b. Distributed Wind and Photovoltaic Power Capacity Constraints That Could Be Connected to the Nodes

\[
G_{n,\min} \leq G_{w,n} \leq G_{n,\max}
\]

\[
G_{n,\min} \leq G_{pv,n} \leq G_{n,\max}
\]

\[
G_{n,\min} \leq (G_{w,n} + G_{pv,n}) \leq G_{n,\max}
\]

where, \( G_{n,\min} \) refers to the minimum installed capacity of distributed wind and photovoltaic power that the access conditions of the \( n \)th node allow to connect, and \( G_{n,\max} \) refers to the maximum installed capacity of distributed wind and photovoltaic power that the access conditions of the \( n \)th node allow to connect.

#### c. Consumption Scope Constraints

- Scenario 1: Complete Consumption in Local Site

For each node \( n \), the constraint conditions are shown in Equation 6:

\[
\min_{0 < t < T} (S_{nl,t} - P_{nl,t} \times G_{w,n} - P_{nl,t} \times G_{pv,n}) > 0
\]

where, \( S_{nl,t} \) refers to the load of the \( n \)th node, \( P_{nl,t} \) refers to the output characteristics of distributed wind power, and \( P_{nl,t} \) refers to the output characteristics of distributed photovoltaic power station.

- Scenario 2: Complete Consumption in Local Station

For each node \( n \), the constraint conditions are shown in Equation 7:

\[
\min_{0 < t < T} (S_{nl,t} - P_{nl,t} \times G_{w,n} - P_{nl,t} \times G_{pv,n}) \leq S_{nl,max}
\]

where, \( S_{nl,max} \) refers to the maximum delivery and transformation capacity allowed for the up-sending branch associated with the \( n \)th node and the \( m \)th node.

- Scenario 3: Redundant Electricity Delivery after Consumption in the Local Station

For each node \( n \), the constraint conditions are shown in Equation 8:

\[
\min_{0 < t < T} (S_{nl,t} - P_{nl,t} \times \sum_{i=1}^{N} G_{w,i} - P_{nl,t} \times \sum_{i=1}^{N} G_{pv,i}) \leq S_{nl,max}
\]

For the entire regional power distribution network, the constraint conditions are shown in Equation 9:

\[
\min_{0 < t < T} (S_{nl,t} - P_{nl,t} \times \sum_{i=1}^{N} G_{w,i} - P_{nl,t} \times \sum_{i=1}^{N} G_{pv,i}) \leq S_{nl,max}
\]

where, \( S_{nl,t} \) refers to the value of the entire regional distribution network load at the moment of ‘t’, and \( S_{nl,max} \) refers to the delivery and transformation capacity of the delivery channel in the entire regional distribution network.

- Scenario 4: Considering Certain Proportion of Power Abandonment in Consumption

For each node \( n \), the constraint conditions are shown in Equation 10-15:

\[
\min_{0 < t < T} (S_{nl,t} - P_{nl,t} \times G_{w,n} - P_{nl,t} \times G_{pv,n}) \leq S_{nl,max}
\]

For the entire regional power grid:
\[
\begin{align*}
\min_{t \in [1, T]} \left\{ S_{\Sigma,1} - P_{\Sigma,1} + \sum_{n=1}^{N} G_{\Sigma,n} - P_{\Sigma,n} + \sum_{n=1}^{N} G_{\Sigma,n}^p - P_{\Sigma,n}^p \right\} \leq S_{\Sigma,\max} \\
Q_{\Sigma,1} = S_{\Sigma,1} + S_{\Sigma,\max} - P_{\Sigma,1} - P_{\Sigma,n} + \sum_{n=1}^{N} G_{\Sigma,n}^p - P_{\Sigma,n}^p \\
Q_{q,1} = \begin{cases} 0 , & Q_{q,1} \geq 0 \\ Q_{q,1} , & Q_{q,1} < 0 \end{cases} \\
\int Q_{q,1} dt \leq k\% \\
\int Q_{f,1} dt \cdot T \leq Q_{dt} \\
\end{align*}
\]  
\hspace{1cm} (11) 
\hspace{1cm} (12) 
\hspace{1cm} (13) 
\hspace{1cm} (14) 
\hspace{1cm} (15) 

where, \( Q_{\Sigma,1} \) refers to the difference between the overall distribution channel of the regional distribution network and the overall distribution power of distributed wind and photovoltaic power at the moment of \( t \), \( Q_{q,1} \) refers to the abandoned power of distributed wind and photovoltaic power at the moment of \( t \), \( Q_{f,1} \) refers to power generation of distributed wind and photovoltaic power at the moment of \( t \), and \( k\% \) refers to the power abandonment rate of distributed wind and photovoltaic power in the 0-T time domain.

3.3. Model Solving

According to the characteristics of the model in this paper, we used the python language with high development efficiency, good extensibility and flexible application for programming and solving. In terms of data input and model solving algorithms, we adopted different methods in combination with different scenarios. For scenario 1, the distributed wind and photovoltaic power of each node is consumed locally, and the nodes are independent of each other, therefore, we adopted the dynamic programming algorithm for solving; for scenario 2 and scenario 3, there is a mutual assistance correlation of the access conditions and consumption space among various nodes, and considering that the distribution network is mostly in radial shape, we searched by using the tree traversal method, and used correlative nodes backtracking method for solving; for scenario 4, we adopted the dynamic optimizing method for solving.

The model solving process in this paper is specifically shown in Figure 1.
4. Calculation Examples

4.1. Introduction to Calculating Example

In this paper, we used a county-level power grid as the research object, and use the node at 110kV voltage level of a 220kV substation as the apex of network topology of the regional distribution network. This 220kV substation is connected with other three 110kV stations in radial pattern, and contacted with other four 35kV stations, of which the schematic diagram of network topology is shown in Figure 2, and the relevant parameters of lines and nodes are shown in Table 1 and Table 2.

4.1.1. Network Topology

The network topology of the regional distribution network in this calculation example is shown in Figure 2.

| Serial No. | Line Name | Voltage Level (kV) | Line Model |
|------------|-----------|--------------------|------------|
| 1          | L-1       | 115                | LGJ-240    |
| 2          | L-2       | 115                | LGJ-240    |
| 3          | L-3       | 115                | LGJ-240    |
| 4          | L-4       | 37                 | LGJ-150    |
| 5          | L-5       | 37                 | LGJ-150    |
| 6          | L-6       | 37                 | LGJ-120    |
| 7          | L-7       | 37                 | LGJ-150    |
| 8          | L-8       | 37                 | LGJ-185    |

Table 2. Node Parameters of the Distribution Network in the Calculation Example

| Serial No. | Name | Voltage Level (kV) | Access Conditions | Maximum Load (MW) |
|------------|------|--------------------|-------------------|-------------------|
| 1          | B-1  | 115                | 1                 | 0                 |
| 2          | B-2  | 115                | 0                 | 0                 |
| 3          | B-3  | 37                 | 1                 | 10                |
| 4          | B-4  | 115                | 0                 | 0                 |
| 5          | B-5  | 37                 | 2                 | 20                |
| 6          | B-6  | 115                | 0                 | 0                 |
| 7          | B-7  | 37                 | 2                 | 8                 |
| 8          | B-8  | 37                 | 1                 | 10                |
| 9          | B-9  | 37                 | 1                 | 0                 |
| 10         | B-10 | 10.5               | 3                 | 5                 |
| 11         | B-11 | 10.5               | 2                 | 6                 |
| 12         | B-12 | 37                 | 0                 | 0                 |
| 13         | B-13 | 10.5               | 2                 | 4                 |
| 14         | B-14 | 37                 | 0                 | 0                 |
| 15         | B-15 | 10.5               | 2                 | 4                 |
| 16         | B-16 | 37                 | 0                 | 2                 |
| 17         | B-17 | 10.5               | 2                 | 6                 |
| 18         | B-18 | 37                 | 0                 | 2                 |
| 19         | B-19 | 10.5               | 2                 | 6                 |
| 20         | B-20 | 230                | 0                 | 0                 |
| 21         | B-21 | 10.5               | 0                 | 0                 |
4.1.2. Load and Distributed Wind and Photovoltaic Power Input Data

The power load in this calculation example includes three types of load characteristics. The typical daily curves of load characteristics and distributed wind power and photovoltaic output characteristics in each season are shown in Figure 3.

![Typical Daily Curves of Load and Distributed Wind and Photovoltaic Power in Four Seasons](image)

**Figure 3. Typical Daily Curves of Load and Distributed Wind and Photovoltaic Power in Four Seasons**

4.1.3. Multi-Scenario Calculation Mode Boundary Conditions and Measurement Results

In the calculation example, we set three scenarios for the new energy categories, i.e., only including wind power, only including photovoltaic power, as well as including both wind power and photovoltaic power, and conducted the simulation calculation of distributed wind and photovoltaic power consumption capacity of the regional distribution network in the four scenarios described above, for which the boundary conditions that need to be explained are as follows: in scenario 3, the allowable delivery capacity was set to be 50MVA; in scenario 4, the power abandonment rate was set to not higher than 5% during the time domain for calculation. The analysis results for scenarios 1 to 4 are shown in Table 3, among which the layout optimization results of distributed wind power and photovoltaic in scenario 1 and scenario 3 are shown in Figures 4 and 5, while the time series production simulation curve of scenario 4 is shown in Figure 6.

**Table 3. Distributed Wind Power and Photovoltaic Power Accommodation Capability Results of Distribution Network in Multi-Scenario Modes**

| Scenario Mode | Wind Power Only (MW) | Photovoltaic Only (MW) | Both Wind and Photovoltaic (MW) |
|---------------|-----------------------|------------------------|---------------------------------|
| Scenario 1    | 48.5                  | 51                     | 75                              |
| Scenario 2    | 53                    | 56.5                   | 83.5                            |
| Scenario 3    | 117.5                 | 113.5                  | 168.5                           |
| Scenario 4    | 182                   | 161                    | 229.5                           |
4.2. Results Analysis

It could be observed from Table 3 that, among these three modes, the distributed new energy accommodation capacities of the regional power grid in the modes including only wind power or only photovoltaic power are lower than that of the distributed wind power and photovoltaic power coexistence mode, therefore, we could conclude that the distributed wind power and photovoltaic power have certain complementary coupling feature in respect to the output characteristics. The total volume of distributed wind power and photovoltaic power that could be accommodated by the regional power grid has gradually increased from Scenario 1 to Scenario 4. Scenarios 1 and 2 have little difference in the distributed wind power and photovoltaic power capacity that could be accommodated by regional distribution network, while Scenarios 3 and 4 both took into account to make the regional power grid to allow certain volume of power to be returned, which improved the accommodation capacity that could be accommodated by the distribution network compared to the measured results in Scenarios 1 and 2; it could be seen from Figure 6 that, in scenario 4, after considering a power abandonment rate of 5% based on scenario 3, the power abandonment volume mostly occurred during periods of low load and the peak time of distributed wind and photovoltaic power generation, therefore, allowing a small volume of power abandonment greatly enhanced the distributed wind power and photovoltaic power accommodation capacity of the regional power grid,
and provided supports for load increase and distributed wind power and photovoltaic planning in later period.

5. Conclusion
With the large-scale access of distributed new energy into the medium and low voltage power grid, the scientific planning of grid-connected solutions for the distributed wind power and photovoltaic power are required to be coordinated. From the perspective of practical application, this paper proposed a method for evaluating the distributed wind power and photovoltaic power accommodation capacity of regional power grids based on the time series production simulation, which made full use of the complementary characteristics of distributed wind and photovoltaic power output, and maximized the mutual assistance of access conditions and consumption space between sites, and conducted multi-scenario distributed new energy consumption capacity sensitivity calculation from the point of the accommodation scope of the distributed new energy. Through combining the calculation results in multiple scenarios, it is recommended that in the planning stage of distributed wind and photovoltaic power in the regional grid, the differences and complementarity of loads between sites should be fully taken into account, which should be combined with future load growth, power grid development and other factors, to allow certain degree of power abandonment, in order to improve the distributed wind and photovoltaic power accommodation capacity of the regional grid, and to provide forward-looking theoretical supports for distributed wind and photovoltaic power planning as well as scientific grid connection.

6. References
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