Research on Optimal Access Location and Capacity of Multi-Stage Multi-Scenario Distributed Power Supply Based on OpenDSS

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Abstract. At present, the research on the planning problem of distributed power access distribution network is mostly carried out under the condition that the target annual load is known, and the impact of the differential load growth in different stages and the multi-scenario timing characteristics of the distribution network components are not considered. Aiming at this problem, an optimal access location and capacity calculation method for multi-period and multi-scenario distributed power supply based on OpenDSS is proposed. Firstly, the simulation principle and advantages of OpenDSS are explained from the aspects of model construction and power flow calculation. Secondly, the optimal power supply access model with multiple time slots and multiple scenarios is established with the goal of minimum planning end value. Thirdly, a model solving method based on particle swarm optimization is proposed. Finally, a typical example is chosen to calculate the optimal planning scheme of distributed power supply under multi-period, and the rationality of the model is verified.

Keywords: Distributed Generation, OpenDSS Simulation, Optimal Access.

1. Introduction

For a long time, the irrationality of the energy structure and the continued low energy efficiency have brought many environmental and social problems. With the liberalization of power policy, distributed generation (DG) as a green and efficient power generation mode presents a large-scale development trend: on the one hand, the development of regional integrated energy systems drives the connection of more distributed power sources. On the other hand, under the encouragement of various Chinese “photovoltaic poverty alleviation” policies and photovoltaic priority grid-connected policies, there will be a large number of distributed power sources connected to the distribution network. Under different access locations and capacities, distributed power sources have different effects on the voltage and network loss of the distribution network. Therefore, it is necessary to combine the effective simulation software and the actual network structure to study the impact of the access location and capacity of the distributed power supply on the distribution network.
At present, domestic and foreign scholars have carried out a series of research on the optimal access problem of DG and achieved relevant results. The literature [1], the minimum annual cost of distribution network is taken as the objective function, and the genetic algorithm is used to optimize the position and capacity of DG. The literature [2-3] further considers the impact of DG access on reliability on the basis of economy. The power supply cost is added to the objective function. After further considering the timing characteristics of DG and load, the literature [4] selects several typical scenarios according to the time series characteristics, and uses the genetic algorithm to obtain the optimal planning scheme of DG; the literature [5] considers the wind speed, light intensity and load. The correlation between the two is based on the minimum annual comprehensive cost, and the DG location constant volume model is established by the opportunity constrained programming method. The literature [6] combines the stochastic power flow calculation method with the typical scene method to simulate the impact of DG access. The method of solving DG programming model based on particle swarm optimization is proposed. The literature [7-8] considers the timing characteristics of load and distributed power output, and selects the location and capacity of DG based on coupled multi-scene technology.

From the different perspectives, the above literature establishes the DG optimal access model considering timing characteristics and multiple scenarios. However, the planning scheme is determined based on the known target annual load, and does not consider the actual distribution network load growth. The multi-stage dynamic programming problem of DG is not detailed and detailed. On the other hand, the multi-scenario multi-stage timing power flow calculation after DG access also needs the technical support of the corresponding simulation platform. OpenDSS (The Open Distribution System Simulator) is a comprehensive simulation software developed by the American Electric Power Research Institute for power distribution systems. It has the characteristics of fast calculation, flexible and scalable, and can be well applied to a large number of distributions. Time-of-flight simulation of power supply access in this new situation: The literature [9] used OpenDSS software to compare and analyze the effects of distributed PV access with different penetration rates on distribution system voltage; The paper [10] analyzed PV through OpenDSS platform. The grid voltage, active power flow and line loss of the industrial park after the grid connection, but did not get the general conclusion, and did not combine with the DG optimal access model to get the optimal DG planning scheme.

Based on this, this paper proposes an open DSS-based multi-segment multi-scenario distributed power optimal access location and capacity calculation method. Combined with OpenDSS simulation platform for multi-scenario time series power flow calculation after distributed wind turbine and photovoltaic access; and proposed DG multi-stage dynamic programming model with minimum annual comprehensive cost as the target and particle swarm algorithm based model solving algorithm; using MATLAB to DG Planning model programming implementation, nested with OpenDSS to achieve multi-stage and multi-scenario optimal access scheme determination; Finally, select typical examples for multi-stage DG planning, which proves the practicability of the proposed model and method. Effectiveness.

2. OpenDSS simulation principle
The simulation process of distributed power supply distribution network using OpenDSS mainly includes data collection, component model construction, power flow calculation, and result analysis. This paper introduces the principle from the two aspects of component model and power flow calculation. Please remember that all the papers must be in English and without orthographic errors.

2.1. Component Model
The OpenDSS provides a rich library of components. The component models are mainly divided into four categories: power conversion components, power transmission components, control components, and measurement components. This paper takes the power supply and distributed generation system as an example to illustrate the modeling principle of OpenDSS components.
2.1.1. Power Supply. The internal mechanical structure of the component is not directly considered in the OpenDSS power supply model, but rather as a whole to describe its external characteristics. The voltage and current characteristics of its access to the grid are represented by Norton equivalent circuits, including constant admittance representing the linear portion of the component and injection current representing the nonlinear portion of the component. The model structure is shown in Fig. 1.

![Figure 1. Principle of power source modeling](image)

2.1.2. Distributed Generation System. Usually, the wind power generation system can be described by the generator model, and the photovoltaic power generation unit needs to be remodeled. The photovoltaic power generation unit is divided into two parts: the photovoltaic panel and the inverter [11], and the component model is shown in Fig.2

![Figure 2. PV system component model](image)

In the Fig.2, $P_{mpp}$ is the reference value of the output power of the photovoltaic array when the irradiance is 1kW/m$^2$ at a certain temperature, $T$ is the current temperature, $I_{rr}$ is the current radiance, $F_T$ is the output power coefficient, and its magnitude is related to temperature. The power $P_{PV}$ emitted by the photovoltaic panel can be obtained by the formula (1).

$$P_{PV} = I_{rr} \cdot P_{mpp} \cdot F_T$$  \hspace{1cm} (1)

Taking into account the inverter losses, the output of the entire photovoltaic system is:

$$P_n = P_{PV} \cdot E_{FP}$$  \hspace{1cm} (2)

Where $E_{FP}$ is the inverter efficiency factor. The reactive power output by the photovoltaic system can be determined by a given power factor or by directly giving the reactive power.
2.2. Power Flow Calculation Based on Gaussian Iterative Method

After modeling each component, a system admittance matrix can be formed, and the power flow calculation is further performed on the entire network. The power flow calculation module of OpenDSS includes basic power flow calculation, running power flow calculation, and random power flow calculation. Based on the component model in multiple scenarios, the Gaussian iterative algorithm is used to calculate the timing power flow. The basic steps are as follows:

Step 1: Calculate the initial value of the node voltage of the system;
Step 2: Form a system admittance matrix, which is divided into two types: a power conversion element (PC) and a power transmission element (PD);
Step 3: Calculate the injection current value of each PC component to form an injection current vector;
Step 4: Solving the system matrix equation to obtain the node voltage value of the current iteration;
Step 5: Determine whether the iteration converges, and if it converges, stop iterating the output calculation result, otherwise return to step 3 until the maximum allowable number of iterations set by the system is reached.

3. Multi-period multi-scenario distributed power optimal access model

The planning period of the actual distribution network is long. If the optimal access scheme of the DG is determined only based on the parameters such as the load conditions of the target year, it cannot reflect the actual optimal capacity calculation scheme of the DG in the middle annual load growth process. The results have certain limitations. Therefore, this paper proposes an optimal access model for distributed power supply in multi-period and multi-scenarios. The planning period is divided into different load development stages. Combined with the simulation results of OpenDSS in multiple scenarios, the DG optimal connection is determined at different time periods. Into the program, and then get the DG dynamic planning results during the overall planning period to achieve the best economic performance.

3.1. Objective Function

The minimum value of the comprehensive cost of the planning period is the objective function, which includes the investment, operation and maintenance costs and residual value of distributed wind turbines and photovoltaics, and the electricity purchase cost of the distribution grid to the upper power grid, as follows:

\[
\min C = C_{PV} + C_{WTG} + C_{OP}
\]

Where, \( C_{PV} \) represents the final life cycle cost of the distributed PV, \( C_{WTG} \) represents the final life cycle cost of the distributed wind turbine, and \( C_{OP} \) represents the final value of the purchased electricity cost during the planning period. The calculation methods of \( C_{PV} \) and \( C_{WTG} \) are as follows:

\[
C_{PV} = \sum_{t=1}^{T} \sum_{i=1}^{N_{PV}} R_{PV} \beta_{i,t} I_i \left( \frac{r(1+r)^m}{(1+r)^m - 1} + u_{PV} - \frac{z_{PV} r}{(1+r)^m - 1} \right)
\]

\[
C_{WTG} = \sum_{t=1}^{T} \sum_{i=1}^{N_{WTG}} R_{WTG} \gamma_{i,t} I_i \left( \frac{r(1+r)^n}{(1+r)^n - 1} + u_{WTG} - \frac{z_{WTG} r}{(1+r)^n - 1} \right)
\]

Where \( T \) is the total number of planning stages; \( N_{PV} \) and \( N_{WTG} \) respectively represent the total number of locations to be built for PV and fans in the distribution network; \( R_{PV} \) and \( R_{WTG} \) respectively represent the cost of construction of a single group of PV or fans; \( \beta_{i,t} \) and \( \gamma_{i,t} \) respectively Indicate the number of PV and fans in position \( i \) of the planning stage \( t \); \( r \) is the social discount rate; \( m \) and \( n \) respectively represent the life of photovoltaics and fans; \( u_{PV} \) and \( u_{WTG} \) represent the proportion of maintenance costs of photovoltaics and fans; \( z_{PV} \) and \( z_{WTG} \) respectively The ratio of residual cost of photovoltaics to wind turbines; \( I_i \) is the final value conversion factor\(^{[14]}\), which is calculated as follows:
\[ I_t = \left[1 - (1 + r)^{-n_t}\right] / \left[r(1 + r)^{a_t-a_T}\right] \]  \hspace{1cm} (6) 

Where \( n_t \) is the number of years in the \( t \)-th phase, \( a_t \) is the initial year of the \( t \)th phase, and \( a_T \) is the year of termination of the planning period.

The final value of the electricity purchase cost of the distribution network to the higher-level power grid during the planning period is as follows:

\[ C_{OP} = \sum_{t=1}^{T} \sum_{\tau=1}^{S_{end}} \sum_{K \in K} \beta_{i,t} R_i \]  \hspace{1cm} (7) 

In the formula, \( S_{end} \) is the total number of years of the scene, including four typical scenes in spring, summer, autumn and winter; \( \tau_{end} \) represents the number of hours in a scene; \( C_P \) represents the price of electricity; and \( W_{tr} \) represents the purchase of the grid to the upper grid in the \( s \)th scene of the \( t \)-stage.

The electricity quantity is composed of three parts: load amount, DG power generation and line network loss. The calculation method is as follows:

\[ W_{tr} = h_t \sum_{k \in K} L_{k,t} \beta_{i,t} \]  \hspace{1cm} (8) 

Where \( h_t \) represents the load growth rate of the \( t \)-th phase compared with the planning start year; \( L_{k,t} \) represents the initial load of the \( k \)th load point at time \( \tau \) in the \( s \) scene; \( K \) represents the load point set; \( P_{b}(s,\tau) \) represents the real-time output of a single group of photovoltaics at time \( \tau \) in the \( s \) scene; \( P_{wind}(s,\tau) \) represents the real-time output of a single group of fans at time \( \tau \) in the \( s \) scene; \( J_i \) represents the distribution line of the distribution network; \( P_{j,s,\tau} \) and \( Q_{j,s,\tau} \) are the active and reactive power flowing through the head end of line \( j \) at time \( \tau \) in the \( s \) scene; \( U_{j,s,\tau} \) is the first segment voltage of line \( j \); \( R_j \) is the resistance of line \( j \).

### 3.2. Restrictions

The optimal access of the distributed power supply in the distribution network needs to ensure the safe and stable operation of the power grid. At the same time, considering the construction sequence of the DG in the multi-period planning process, the main constraints are set as follows:

1) Power flow constraints of the distribution network

\[ P_i = U_i \sum_{j \neq i} U_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \]

\[ Q_i = U_i \sum_{j \neq i} U_j \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) \]  \hspace{1cm} (9) 

In the formula, \( P_i \) and \( Q_i \) are active and reactive injection at node \( i \); \( U_i \) and \( U_j \) are voltage amplitudes of nodes \( i \) and \( j \); \( G_{ij} \) and \( B_{ij} \) are conductance and susceptibility of branch \( ij \); \( \theta_{ij} \) is voltage phase between nodes \( i \) and \( j \).

2) DG investment order constraints

\[ \beta_{i,t} \leq \beta_{i,t+1} \]

\[ \gamma_{i,t} \leq \gamma_{i,t+1} \]  \hspace{1cm} (10) 

3) DG investment order constraints
The constraint condition indicates that the number of photovoltaic or fan groups in the next stage position \( I \) cannot be smaller than the previous stage in the process of DG multi-period planning, that is, a position DG cannot be removed after being built.

3) Node voltage constraint

\[
U_{i\min} < U_i < U_{i\max}
\]  

(11)

The constraint indicates that the voltage amplitude of each node must be between the allowed upper and lower limits of safety at any time during the multi-scenario time series simulation using OpenDSS.

4) Branch current constraint

\[
I_k < I_{k\max}
\]  

(12)

The constraint indicates that the branch current at any time during the tidal simulation cannot exceed the maximum current allowed by the branch.

The optimization object of the distributed power supply optimal access model is the number of PV and fan groups \( \beta_{i,t} \) and \( \gamma_{i,t} \) accessed by different nodes in each stage of the planning period, and the DG access plan can be dynamically adjusted according to the load change. The network maximizes the benefits under the premise of safe operation.

3.3. Solution Algorithm

In this paper, the particle swarm optimization algorithm is used to optimize the DG optimal access model. The solution process is as follows:

Step 1: Input distribution network parameters and particle swarm algorithm parameters, including line topology and resistance, DG candidate nodes, acceleration constants in particle swarm algorithm, inertia factor, constraint factors, etc., and input to distributed photovoltaics, fans, The parameters of the load and other components, the DG output sequence and the load value of each typical day in different scenarios in different stages are obtained.

Step 2: Initialize the particle swarm to determine the initial multi-period DG access scheme.

Step 3: Combine the OpenDSS simulation platform to calculate the timing power flow for each particle corresponding DG planning scheme, obtain the voltage, network loss, power distribution and other information in multiple scenes and multi-period, and calculate the voltage and branch current of each node.

Step 4: Determine whether the constraint condition is met. If the condition is satisfied, the penalty item is set to zero. If it is not satisfied, the penalty is added to the objective function.

Step 5: Combine equation (3) to obtain the optimal value of each particle and the global optimal value of the particle group.

Step 6: Determine whether the particle swarm algorithm satisfies the termination condition, that is, whether the global optimal value converges or reaches the maximum number of iterations, and then outputs the optimal solution and decodes to obtain a multi-stage DG planning scheme, otherwise it proceeds to the next step.

Step 7: Perform a particle swarm update operation to obtain a new particle swarm position and velocity. When updating, adjust the particle encoding to satisfy the discretization requirement of the DG number and the constraint of the construction order, and return to step 3.

4. Case verification and result analysis

4.1. Overview of the Study

In this paper, the IEEE33 node typical example \(^{[12]}\) is simulated and analyzed. The system structure is shown in Fig 3. The system consists of 32 branches and 33 nodes. The distance between adjacent nodes is set to 1km. The initial peak load of the line, node data and each load point is shown in Table A1 of
Appendix A. Node 1 is the bus node and the power network. The head end reference voltage is 12.66kV. Nodes 7, 8, 21, and 22 are distributed installation candidates for distributed fans, and nodes 18, 21, and 30 are distributed PV candidate nodes.

The planning period is 20 years. It is divided into four planning stages, with 5, 10 and 15 years as the dividing line. The load growth rate of the subsequent stage compared with the initial stage is 63%, 176% and 260% respectively. The load growth trend is an S-shaped curve. In terms of distributed photovoltaic parameters: the parameters $R_c$ and $G_{std}$ of the photovoltaic output model are 0.15 kW/m$^2$ and 1 kW/m$^2$, respectively, the rated power of a single set of photovoltaics is 100 kW, and the investment cost per unit capacity is 1.05 million yuan /kW. The cost ratio is 10%, and the residual cost ratio is 4%. Fan parameters: cut-in, rated and cut-out wind speed are 3,13,20m/s, single fan rated power 100kW, unit capacity investment cost is 0.9 million yuan / kW, maintenance cost ratio 12%, residual value The cost ratio is 6%. The service life of photovoltaics and fans is set at 30 years, and the discount rate is 0.06.

The electricity purchase cost of the distribution network is 0.35 yuan/kWh, and the typical days and days of the four types of scenes in spring, summer, autumn and winter are 87, 121, 73 and 84 respectively. The allowable range of the node voltage is 0.9−1.1 (standard value), all the maximum allowable current of the branch is 1.2kA. The population size of the particle swarm is taken as 20, and the maximum number of iterations is set to 100.

4.2. Influence of Distributed Power Access on Node Voltage
Assuming that the distance between adjacent nodes is 1km, the simulation method is to add distributed photovoltaic at the end of the line (18 nodes), and increase the photovoltaic capacity in steps of 100kW from 0kW until the system voltage exceeds the limit, and obtain distributed photovoltaic. The instantaneous power flow calculation results before the access and when the voltage is exceeded are shown in Fig.4.
The blue fold line shown in Fig.4 corresponds to the voltage standard value of each line. The voltage reference value is 12.66kV, where node 1 is connected to the grid, assuming that its voltage is always the same as the large grid.

The threshold value of the distributed PV capacity that is connected to the 18 nodes so that the voltage is just over the limit is 2100 kW. The voltage distribution of the system before and after the distributed PV access can be seen and analyzed. The node voltage of the entire network after distributed PV access can be seen. All of them are uplifted, and their elevation is related to the relative position of the nodes and distributed PV access nodes: from the lateral comparison of the branches, the node voltage of the distributed PV is affected by the branch voltage is greater than other branches; In the longitudinal comparison of the branches, the closer the distance from the distributed power source is, the more the voltage is affected.

4.3. Optimization Result of Optimal Access Model
The MATLAB programming is used to optimize the particle swarm, and the OpenDSS is continuously called to simulate the power flow. The objective function and constraints are calculated, and the DG optimal access model is optimized. The optimal DG access plan for different planning stages is shown in Table 1.

| Plan Stage | Fan Node[number] | PV node[number] | Objective Function Ten Thousand Yuan |
|------------|------------------|----------------|--------------------------------------|
| 1          | [8][1],21[1]     | 18[1]          | 3687.47                              |
| 2          | [7],8[2],21[2]   | 18[1],30[2]    | 5261.80                              |
| 3          | [7],8[2],21[4],22[1] | 18[3],30[2]    | 6989.14                              |
| 4          | [7],8[2],21[4],22[1] | 18[4],21[2],30[4] | 8146.23                              |

It can be seen from Table 1 that the model proposed in this paper can realize multi-stage planning of distributed wind turbines and photovoltaics in the distribution network. Combining the load development levels of different stages, determine the appropriate DG optimal access scheme to achieve flexible and dynamic access of DG during the development of the distribution network.

Further compare the final value of the target annual comprehensive cost under different planning schemes, the specific scheme is as follows:

Option 1: Do not install DG;
Option 2: Install only the fan;
Option 3: Install only photovoltaics;
Option 4: Multi-scenario timing characteristics without considering the load;
Option 5: Do not consider multi-stage planning; Option 6: Do not consider the multi-scenario timing characteristics of the load or the multi-stage planning; Scheme 7: The proposed scheme in this paper considers multiple scenarios and multiple scenarios at the same time.

The results of the target year planning under different scenarios are shown in Table 2:

| Plan Stage | Fan Node[number] | PV node[number] | Objective Function Ten Thousand Yuan |
|------------|------------------|----------------|--------------------------------------|
| 1          | ---              | ---            | 10680.11                             |
| 2          | [7][3],22[3]    | 18[4],21[3],30[5] | 9067.50                              |
| 3          | ---              | 18[4],21[3],30[5] | 9413.58                              |
| 4          | [7][3],22[3]    | 18[1],21[3]    | 11306.80                             |
| 5          | [7],8[2],21[4],22[1] | 18[4],21[2],30[4] | 12437.28                             |
| 6          | [7],8[3],21[2]  | 18[3],21[3],30[2] | 14218.94                             |
| 7          | [7],8[2],21[4],22[1] | 18[4],21[2],30[4] | 8146.23                              |
Comparing schemes 1, 2, 3 and scheme 7, it can be found that planning the wind turbine and photovoltaic at the same time can reduce the final comprehensive cost. Although there are certain construction and operation costs after installing DG, reasonable selection of capacity can effectively reduce the network loss and network supply load, thereby improving the economy as a whole, and the complementary characteristics of the fan and photovoltaic can also improve the network's power flow distribution. Therefore, it is necessary to properly access the DG in the distribution network.

Comparing schemes 4 and 7, it can be found that the objective function value after considering the multi-scene timing characteristics of the load is significantly better, which is due to the consideration of the complementarity and coupling of wind speed, light intensity and load at different time periods. Compared with scheme 5 and scheme 7, under the multi-stage dynamic planning, the reduction effect of the comprehensive cost in the planning period is more obvious, and the planning result is more loaded with the development of the actual grid. The comparison of different schemes in the table proves the rationality and effectiveness of the multi-period multi-scenario DG optimal access model proposed in this paper.

5. Conclusion

This paper proposes a distributed power supply optimal access model considering multi-period and multi-scenarios: using OpenDSS for time-series power flow simulation in multiple scenarios, which can accurately analyze the impact of DG access on distribution network power flow distribution; The minimum final cost of the planning period is the target. Considering the power flow constraints such as node voltage and branch current and the construction order constraints of DG dynamic programming, the DG optimal access model in multi-scenario and multi-scenario is proposed. Optimized solution, through the repeated calls of MATLAB and OpenDSS to achieve the optimal access plan.

The results of the example show that the OpenDSS simulation platform can accurately analyze the influence of different positions and capacities of DG on the voltage and network loss of the distribution network under multi-scenario timing conditions. Combined with the optimal access model, the dynamic load growth process during the planning period can be obtained. The multi-stage optimal planning scheme, compared with the traditional target annual overall planning scheme, considers the multi-period and multi-scenario DG location and volumetric scheme to significantly reduce the comprehensive operating cost and improve the economy of the distribution network after distributed power access.

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