Bi-level planning for distribution network including distributed generations and electric vehicle charging stations to meet the requirements of internet of things construction

Feng Li¹, Jianjie Li¹, Ziyang Han²*, Ping Li¹, Peng Li¹, Wentao Zhong¹ and Zihan Meng²

¹ State Grid Binzhou Electric Power Supply Company, Binzhou, Shandong Province, 256699, China
² Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, 300072, China
*Corresponding author’s e-mail: hanzy@tju.edu.cn

Abstract. With the development of power internet of things technology, the application of internet of vehicles technology in the field of electric vehicles (EVs) is constantly maturing and improving. In line with the concept of building an environment-friendly society, distributed generations (DGs) and EVs are being built and put into use in large numbers. In this context, in order to improve the accuracy of distribution network planning, this paper proposes a distribution network planning method based on big data technology. The upper layer aims to minimize the present value of the comprehensive cost of the distribution network, and the lower layer aims to minimize the construction, operation, and maintenance costs of electric vehicle charging stations (EVCSs) and DGs. Under the constraint of relevant constraints, the optimal grid structure of the distribution network including DGs and EVCSs is obtained. The effectiveness of the proposed method is demonstrated using a 54-bus distribution system.

1. Introduction
In recent years, with the development of economy, environmental pollution has become increasingly serious. In order to alleviate this situation, the DG with the advantages of clean and environmental has been developed rapidly[1]. In addition, due to the serious environmental problems caused by fuel vehicle emissions, EVs will become the mainstream of urban transportation in the future[2]. In the context of internet of things and big data, EV charging and replacement infrastructure and service information are the core advantageous resources to meet the rigid demand of EV users, which is conducive to entering the EV internet market[3, 4].

The distribution network is the closest part of the power system to users. Reasonable distribution network planning can not only bring huge social benefits, but also improve the economy and security of the power network operation. In [5], on the basis of considering the scheduling and operation of controllable DGs and interruptible loads, and taking into account the planning and operation process of distribution network, a bi-level optimization method of distribution network is proposed, which includes the operation of various DGs. In [6], a road network traffic satisfaction model based on the path location model and site selection evaluation model is constructed, and a multi-objective site selection and constant volume optimization planning model for EVCSs and DGs is established on the basis of considering the output timing characteristics and complementarity of DGs. With the
development of power big data theory and method, making full use of power big data to realize accurate planning of distribution network is the current development trend of power network planning.

In order to realize the accurate planning of the distribution network, this paper considers the load prediction of the distribution network and the site selection of the substation based on the power big data, and carries out the distribution network planning according to the situation that the DGs and EVCSs are connected at the same time, so as to find the distribution network structure with the minimum cost.

2. Bi-level planning model for distribution networks

In this paper, a bi-level planning model is established on the basis of considering DGs and EVCSs, as shown in figure 1.

2.1. Upper model

2.1.1. Objective function. After the use of big data technology to predict load and substation pre-site selection, the objective function of the upper distribution network planning is as follows:

$$\min F_1 = C_{\text{inv}} + C_{\text{main}} + C_{\text{ope}}$$  \hspace{1cm} (1)

where $C_{\text{inv}}$ represents the investment cost, which refers to the present value of the investment cost required by the new line and substation; $C_{\text{main}}$ represents the maintenance cost, which refers to the present value of the maintenance cost required by the line and substation; $C_{\text{ope}}$ represents the cost of buying electricity from the upper grid.

$$C_{\text{inv}} = C_{\text{inv}}^1 + (1 + r)^{-n_y} C_{\text{inv}}^2$$  \hspace{1cm} (2)

$$C_{\text{inv}}^y = C_{L}^y + C_{\text{SUB}}^y$$  \hspace{1cm} (3)

$$C_{L}^y = \sum_{i=1}^{I} \sum_{j=1}^{J} x_{ij} C_{ij}$$  \hspace{1cm} (4)

$$C_{\text{SUB}}^y = \sum_{s=1}^{S} \sum_{q=1}^{Q} x_{sq} C_{q}$$  \hspace{1cm} (5)

Where $C_{\text{inv}}^1$ is the investment cost of the first stage planning; $r$ is the annual interest rate; $n_y$ is the number of years in the planning period; $C_{\text{inv}}^2$ is the investment cost of the second stage planning; $C_{\text{main}}^y$ is the investment cost of the second stage planning; $y$ is the number of planning periods, $\forall y \in \{1, 2\}$; $C_{ij}$ is the construction and upgrading cost of the power distribution line in stage $y$; $C_{\text{SUB}}^y$ is the construction and upgrading cost of the substation in stage $y$; $C_{ij}$ is the construction cost of type $i$ of line $j$; $I$ is the set of lines to be created; $J$ is the set of line types; $C_{q}$ is the construction cost of $q$ type substation; $S$ is the number of substation sites determined by the big data algorithm; $Q$ is the set of substation types; $x_{ij}$ and $x_{sq}$ are ‘0-1’ state variables, which respectively represent the construction variables of the line and substation. If they are 1, the construction will be implemented; otherwise, the construction will not be implemented.

$$C_{\text{main}} = C_{\text{main}}^1 + (1 + r)^{-n_y} C_{\text{main}}^2$$  \hspace{1cm} (6)

$$C_{\text{main}}^y = n_y (\alpha_L \sum_{i} C_{L}^y + \alpha_{\text{SUB}} \sum_{i} C_{\text{SUB}}^y)$$  \hspace{1cm} (7)
Where $C_{\text{main}}$ is the maintenance cost of the first stage planning; $C_{\text{main}}^2$ is the maintenance cost of the second stage planning; $\alpha_L$ is the annual maintenance cost coefficient of the line; $\alpha_{\text{SUB}}$ is the annual maintenance cost coefficient of the substation.

\[ C_{\text{ope}} = 2n_D \sum_{t=1}^{24} p_t P_{\text{buy},t} \]  

(8)

Where $p_t$ is the electricity price at time $t$; $D$ is the number of days in an operating cycle, calculated with one year as an operating cycle, taken as 365 days; $P_{\text{buy},t}$ is the power purchased from the upper grid at time $t$.

2.1.2. Model constraints

1) Power flow constraint:

\[ P_i = \sum_{j=1}^{n} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \]

\[ Q_i = \sum_{j=1}^{n} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \]  

(9)

where $P_i$ and $Q_i$ are the injected active and reactive power of node $i$ respectively; $V_i$ is the voltage amplitude of node $i$; $G_{ij}$ and $B_{ij}$ are the real and imaginary parts of the node admittance matrix respectively; $\theta_{ij}$ is the voltage phase angle difference between node $i$ and $j$.

2) Branch transmission power constraint:

\[ P_{ij,t}^{\text{max}} \leq P_{ij,t} \leq P_{ij,t}^{\text{min}} \]  

(10)

where $P_{ij,t}$ is the transmission power of branch $ij$ at time $t$; $P_{ij,t}^{\text{max}}$ and $P_{ij,t}^{\text{min}}$ are the maximum and minimum transmission power of branch $ij$, respectively.

3) Distribution network radial constraint

2.2. Lower model

2.2.1. Objective function. The objective function of the lower model is as follows:

\[ \min F_2 = C_{\text{EV}} + \sum_{e=1}^{E} C_{\text{E-ope}} P_{\text{E-ope}} + C_{\text{DG}} + \alpha_{\text{DG}} C_{\text{DG}} + C'_{\text{ope}} \]  

(11)

where $C_{\text{EV}}$ is the construction cost of EVCSs; $C_{\text{E-ope}}$ is the annual maintenance cost of the unit capacity of the EVCS; $P_{\text{E-ope}}$ is the rated capacity of the newly-built EVCS at node $e$; $E$ is the set of EVCSs nodes; $C_{\text{DG}}$ is the cost of construction and upgrade of DG; $\alpha_{\text{DG}}$ is the annual maintenance cost coefficient of DG; $C'_{\text{ope}}$ is the operating cost of EVCSs and DGs.

\[ C_{\text{EV}} = \sum_{e=1}^{E} x_e (C_{\text{E-fix}} + P_{\text{E-ope}} C_{\text{E-vab}}) \]  

(12)

\[ C_{\text{DG}} = \sum_{a=1}^{A} \sum_{a=1}^{W} x_{aw} C_a + \sum_{i=1}^{P} \sum_{p=1}^{P} x_{ip} C_p \]  

(13)

\[ C'_{\text{ope}} = D \sum_{t=1}^{24} p_t P'_{\text{buy},t} \]  

(14)
Where \( C_{E\text{-fix}} \) is the fixed construction cost of EVCS; \( C_{E\text{vab}} \) is the variable construction cost per unit capacity of EVCS; \( C_{w} \) is the construction cost of type \( w \) wind power station; \( A \) is the set of possible wind power station nodes; \( W \) is the total number of wind power station types; \( C_{p} \) is the construction cost of type \( p \) photovoltaic power station; \( C \) is the set of possible photovoltaic power station nodes; \( P \) is the total number of photovoltaic power station types; \( x_{e}, x_{sw} \) and \( x_{cp} \) are ‘0-1’ state variables, which respectively represent the construction variables of EVCS, wind power station and photovoltaic power station. If they are 1, the construction will be implemented; otherwise, the construction will not be implemented. \( P'_{\text{buy,t}} \) is the net power of EVCSs and DGs purchased from the upper grid at time \( t \).

2.2.2. Model constraints.

1) DGs output constraint:
\[
P_{g_{\text{min}}} \leq P_{g,t} \leq P_{g_{\text{max}}}
\]  \( (15) \)

where \( P_{g,t} \) are the output of the DG at time \( t \); \( P_{g_{\text{max}}} \) and \( P_{g_{\text{min}}} \) are respectively the maximum and minimum output power of DG.

2) Capacity demand constraint of EVCSs:
\[
\sum_{e \in C} P_{EVe} \geq P_{de}
\]  \( (16) \)

where \( P_{de} \) is the charging capacity demand of EV, which can be determined according to EV battery pack demand in planned level year.

3) EVCS utilization constraint:
\[
R_{EVe} \geq R_{\text{min}}
\]  \( (17) \)

where \( R_{EVe} \) is the utilization rate of the EVCS of node \( e \); \( R_{\text{min}} \) is the minimum value of the utilization rate of the EVCS. In order to avoid resource waste, the utilization rate of EVCS is analyzed through big data technology, and the utilization rate of charging facilities is required to be no less than the minimum specified utilization rate.

3. Model solving
The upper model is solved by calling Gurobi solver in Python program, so as to obtain the best scheme of the upper distribution network grid planning. Particle swarm optimization algorithm is used to solve the optimal planning scheme of DGs and EVCSs under the current grid structure. The diagram of grid planning is shown in figure 2.
4. Case study

4.1. Case parameter setting

The above distribution network planning method is applied to the 10kV distribution network as shown in figure 3.

In order to verify the proposed planning model and method, the analysis is based on the following assumptions.

(1) Assuming that the total capacity of EVCSs to be built is 1.2MW, it is feasible to construct charging stations at any node;

(2) It is feasible to construct in wind power station and photovoltaic power station at any node. The optional rated capacity (construction cost) of wind power station is 200kW (0.1MUSD) and 400kW (0.2MUSD) respectively. The optional rated capacity (construction cost) of photovoltaic power station is 300kW (0.24MUSD) and 500kW (0.29MUSD) respectively.

The parameters are set as follows: the planning period is 10 years, divided into two stages, each planning period is 5 years; equipment is installed in the initial year of each stage; the load is the forecast result obtained by the load forecasting method based on big data technology; the annual interest rate is 5%; the annual maintenance cost coefficient of the line is 0.04; the annual maintenance cost coefficient of EVCSs is 0.15; the annual maintenance cost coefficient of the DGs and substation is 0.1; the electricity price from the upper grid for peak ((08:00,11:00] ∪ (18:00,23:00]), flat ([07:00,08:00] ∪ (11:00,18:00]), valley ((23:00,24:00] ∪ (00:00,07:00]) is 0.186USD/kW·h, 0.114USD/kW·h, 0.056USD/kW·h.
4.2. Analysis of results
Using the distribution network planning method proposed in this paper, the following four cases are constructed to compare and analyse the planning results.

Case 1: without considering DGs and EVCSs, the distribution network is planned independently. The planning results are shown in Figure 4.

Case 2: without considering EVCSs, the distribution network with DGs is planned. The planning results are shown in Figure 5.

Case 3: without considering DGs, the distribution network including EVCSs is planned. The planning results are shown in Figure 6.

Case 4: The bi-level planning of distribution network including DGs and EVCSs is comprehensively considered. The planning results are shown in Figure 7.

Table 1. Cost comparison of the four planning cases.

| Case | Photovoltaic power station construction node (capacity/kW) | Wind power station construction node (capacity/kW) | EVCSs construction node (capacity/kW) | Investment cost /MUSD | Maintenance cost /MUSD | Operating cost /MUSD | Total cost /MUSD |
|------|----------------------------------------------------------|--------------------------------------------------|--------------------------------------|-----------------------|-----------------------|---------------------|-----------------|
| 1    | 2(500),12(500),3(7(500)                                  | /                                                | /                                    | 2.78                  | 2.10                  | 29.11               | 33.99           |
| 2    | /                                                        | 4(400),17(400),25(400)                           | /                                    | 3.70                  | 3.00                  | 18.70               | 25.40           |
| 3    | /                                                        | /                                                | 8(300),21(300),29(300),48(300)        | 5.50                  | 4.96                  | 32.98               | 43.44           |
| 4    | 2(500),12(500),3(7(500)                                  | 4(400),17(400),25(400)                           | 21(300),30(300),42(300),50(300)       | 5.84                  | 4.97                  | 21.73               | 32.54           |

According to the cost comparison of the four cases in table 1, case 1 does not consider the planning and construction of DGs and EVCSs, so the investment cost and maintenance cost are the lowest. The total cost of case 2 is the lowest, because EVCSs are not considered in case 2. Compared with case 1, it can be seen that although DGs will increase construction and maintenance costs, it can effectively reduce the amount of electricity purchased from the upper grid, which greatly reduces operating costs. This shows that the economic benefits brought by DGs in this paper are greater than expenses required for the construction and maintenance of DGs. The total cost of case 3 is the highest because DGs are not taken into consideration in case 3. The investment cost and maintenance cost of case 4 are the highest, because the DGs and EVCSs are taken into consideration in case 4. Case 4 takes into account DGs, so the operating cost of case 4 is lower.

By analysing planning results, we can find that although the construction cost of the DGs increases along with the capacity of DGs, DGs can bring benefits also will increase, and the benefits of DGs are greater than the cost needed for its building, so in this article, the construction capacity of DGs is selected within a reasonable range of large capacity. In the planning of EVCSs, four nodes are selected to build EVCSs. Four EVCSs have larger service radius, which can alleviates the problem of EV charging difficulties to a certain extent. In addition, the capacity of each charging station is relatively small, which can be expanded as needed in the future.
In summary, case 4 comprehensively considers the bi-level grid planning of the distribution network including DGs and EVCSs, it can determine the location and capacity of DGs and EVCSs at the same time, as well as lines and substations that need to be upgraded or newly built, and obtain the most reasonable planning result, which can achieve the greatest economic benefits with a relatively small cost.

5. Conclusion
Aiming at the distribution network planning under the background of internet of things, this paper uses big data technology for load prediction and substation pre-site selection, and then considers the distribution network planning with DGs and EVCSs. The following conclusions are drawn:

1) Considering DGs and EVCSs at the same time is crucial to the current distribution network planning. A bi-level distribution network programming model with DGs and EVCSs is established.

2) Considering DGs and EVCSs at the same time is conducive to the development of EV industry. The research on the integration of EVCSs has guiding significance for the construction of the internet of vehicles under the background of the internet of things.

3) Through the analysis of the case, it is proved that the planning model proposed in this paper is scientific and feasible.
Based on the research in this paper, the influence of EVCSs on the distribution network and the modelling and coordinated control technology of DGs can be further studied in the future.

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