A collaborative planning method of distribution network including EV charging piles and Distributed Generations

Haiyue Yang¹, Dong Liu²*, Lu Yu², Eryong Liu¹, Xiaohui Mei¹, Shouxiang Wang ²

¹ State Grid Hengshui Electric Supply Company, Hengshui, Hebei, 053000, China
² School of Electrical and Information Engineering, Tianjin University, Tianjin, 300072, China

*Corresponding author’s e-mail: liudong_1996@tju.edu.cn

Abstract. With the growing penetration rate of distributed generations (DGs) and large number of unordered charging electric vehicles (EVs), the distribution network (DN) is facing more challenges than before. Therefore, the DN planning integrated of EVs and DGs is the primely problem. Firstly, an traffic network model and a distributed power supply output model are established to simulate the actual traffic network flow distribution through the principle of user equilibrium flow distribution. Secondly, an improved adaptive free search algorithm is proposed to coordinate site selection planning of EV charging pile and DG considering the factors of economy and users' satisfaction of charging. Finally, taking the modified IEEE 33-node distribution network as an example, the proposed model and algorithm are simulated and verified. The simulation results show that the proposed model and programming method are feasible and effective.

1. Introduction

Energy conservation and emission reduction have become the focus of the society, and the national 13th Five-Year Plan has also put forward higher requirements for energy utilization and environmental protection. The distributed generation (DG) technology of renewable energy and low-consumption electric vehicle EV technology are the two keys, which are used of "energy conservation and emission reduction". However, the output of DG is intermittent and random [1]. At the same time, the access of large-scale EVs will also bring load growth and fluctuation to the distribution network [2], which will further increase the difficulty of distribution network planning and dispatching.

In terms of DG planning, many experts have carried out many researches. In [3], a mathematical model is established for reactive power optimization of a multi-objective distribution network aiming at the uncertainty caused by the access of DG to the DN, and solved the problem by using the orthogonal multi-objective differential evolutionary algorithm. In terms of the construction of EV charging stations, paper [4] takes the small investment and operation cost of the distribution network of charging stations as the target, and establishes a distribution network planning model that takes into account the optimization of the distribution station layout, which can effectively reduce the investment and operation cost, but didn't consider the user's convenience of charging. However, few of the above papers established a unified planning model considering EV with DG together. In [5], DG and EV charging station are considered in planning, and user traffic satisfaction index is proposed, but the traffic network
model doesn’t match the DN model. Therefore, it is necessary to propose a more effective EV-DG collaborative planning strategy.

On the basis of previous studies, this paper mainly carried out the following work.

1) Establish a more realistic traffic network model, propose an optimal path selection model based on the principle of user equilibrium flow distribution, and establish a user satisfaction evaluation objective system.

2) Propose an EV-DG collaborative planning model and establish a double-objective evaluation system from two aspects of economy and user satisfaction.

3) Make a Pareto distribution of optimal configuration scheme through the improved adaptive FS algorithm and verify the effectiveness of the algorithm and planning strategy.

2. Modelling of Traffic Network and Distributed Generation

2.1. Traffic network modeling

The nodes defined in the network represent intersections, and the lines between the nodes represent roads. The length, width and other basic information of the road are represented by zero current cost \((t_a^0)\) and current-carrying capacity \((C_a)\). Among them, the zero-flow cost represents the cost consumed by vehicles passing through the section when the traffic flow is zero, and the current-carrying capacity represents the maximum traffic flow allowed to pass through the section without traffic jams. The traffic flow of section is shown as

\[
x_a = \sum_R \sum_t f_t^R \sigma_{at}, \quad \forall t \in T^R, \forall a \in A
\]

Where, \(R\) and \(t\) respectively represent the set of O-D and a connected path of a certain O-D; \(T^R\) represents the set of connected paths of some O-D pair; \(f_t^R\) represents the traffic flow in the \(t\) path under the O-D; \(\sigma_{at}\) represents a binary number, when the O-D pair of path \(t\) through the section, take 1, otherwise 0; \(A\) represents the section collection of the traffic network.

Through Equation (1), it can be found that the toll of vehicles in a certain section changes in real time according to the traffic flow information of that section. So the road toll is also time - varying. To solve this problem, the US Highway Administration proposed the BPR function based on a large number of statistical data, as shown in Equation (2)[6].

\[
t_a = t_a^0 \left[1 + \alpha \left(\frac{x_a}{C_a}\right)^\beta\right]
\]

Where: \(t_a\) is the actual toll of the road section; \(x_a\) represents the traffic flow of the section; \(\alpha\) and \(\beta\) are the calibration parameters of the model. In the general urban traffic network, \(\alpha = 0.15\) and \(\beta = 4.0\).

2.2. An optimal path selection model based on the principle of user equilibrium distribution

In the path selection problem of traffic network, the optimal path of a certain O-D pair is searched the path with the lowest total travel cost. Common search methods include Dijkstra algorithm, A* algorithm, Dstar algorithm, etc., but their common problem is that the time-varying road passage cost cannot be considered. To solve the above problems, the Wardrop balance principle is selected as the basis of optimal path selection in this paper. Section toll in the equilibrium state has the following relationship with section traffic flow as

\[
\begin{cases}
  u_{ij} - c_{ij}^t = 0, & f_{ij}^t > 0 \\
  \leq 0, & f_{ij}^t = 0
\end{cases}, \quad \forall i, j \in K, \quad t \in T
\]

Where, \(u_{ij}\) represents the minimum toll between \(i\) and \(j\) under equilibrium state. \(c_{ij}^t\) represents the toll of \(t\) paths between \(i\) and \(j\); \(f_{ij}^t\) represents the traffic flow between \(i\) and \(j\); \(K\) represents the set of all nodes in the traffic network; \(T\) represents the set of all the connected paths for a O-D pair.

It can be found from the above formula that when the traffic distribution of the traffic network reaches an equilibrium state, the travel costs of any O-D for all the alternative routes are equal, and travellers
cannot reduce the travel costs by changing the choice of routes. This principle can solve the problem that the optimal path cannot be explored due to the time-varying road toll.

2.3. Distributed generation modeling
The actual output of photovoltaic cells is affected by meteorological factors and non-meteorological factors. According to the statistical analysis, the solar light intensity conforms to Beta distribution in a certain period of time. Combined with the relationship between actual output of photovoltaic cells and temperature and light intensity, the following calculation model is established

$$P_{pv}(t) = \eta P_{p,N} \frac{I}{I_N} \left(1 + \zeta (T(t) - T_N)\right)$$

(4)

Where $\eta$ is the amount of decrease factor caused by non-meteorological factors of pv array, generally 0.9; $P_{p,N}$ is the rated capacity of photovoltaic array; $\zeta$ is the power temperature coefficient; $I$ is the actual light intensity; $I_N$ and $T_N$ represent the rated light intensity and rated surface temperature of photovoltaic cells respectively; $T(t)$ is the actual temperature of the photovoltaic cell at time $t$.

The combined application of energy storage and photovoltaic power supply can effectively solve the instability of photovoltaic power supply output, and greatly improve the power supply reliability of the grid, and improve the ability to resist risks. The output model of the energy storage battery is as

$$P_{battery}(t) = \begin{cases} -\eta_{discharge}(t) \cdot P_{battery,N} & \text{if } \eta_{discharge}(t) > 0 \\ \eta_{charge}(t) \cdot P_{battery,N} & \text{if } \eta_{charge}(t) > 0 \end{cases}$$

(5)

Where $\eta_{discharge}(t)$ and $\eta_{charge}(t)$ are respectively the output efficiency of an energy storage battery at time $t$, which are determined mainly according to the deviation value between the voltage at the installation node of energy storage and the rated voltage. $P_{battery,N}$ is the rated power of the energy storage battery.

3. Collaborative planning strategy based on FS algorithm

3.1. The objective function
(1) Economic index

$$f_1 = \sum_{i \in I} \sum_{j \in I} I^2_{ij}(t) R_{ij} \tau + \sum_{i=1}^{N_i} \sum_{k=1}^{K} \alpha_{lk} C_{DG,k} + \sum_{k=1}^{K} \beta_{lk} C_{VG,k} + P_{buy} \tau$$

(6)

Where $I_{ij}$ is the current value between node $i$ and node $j$; $R_{ij}$ is the resistance value between node $i$ and node $j$; $\tau$ is the electricity price; $\alpha_{lk}$ and $\beta_{lk}$ are the number of Class $k$ DG and EV charging piles at node $i$. $C_{DG,k}$ and $C_{VG,k}$ are the construction cost of class $k$ DG and EV charging pile respectively. $P_{buy}$ represents the total amount of active power that needs to be purchased from the superior grid each year.

(2) Charging satisfaction

$$f_2 = \eta \sum_{m \in M} f_m y_m + (1 - \eta) \sum_{m \in M} d_m X_m$$

(7)

Where $\eta$ represents the weight coefficient, and $0 < \eta < 1$; $m$ and $M$ respectively represent a specific path and the total number of paths; $f_m$ represents the traffic flow of path $m$; $y_m$ is the decision variable. When the number of charging piles meets the traffic flow demand of path $m$, $y_m = 1$; otherwise, $y_m = 0$. $d_m$ represents the path length of section $m$, and $X_m$ represents the number of charging pile facilities in section $m$.

3.2. constraint condition
(1) Flow constraint

$$P_i = V_i \sum_{j \in I} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad Q_i = V_i \sum_{j \in I} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})$$

(8)

(2) Nodal voltage constraint

$$V_{i,\text{min}} \leq V_i \leq V_{i,\text{max}}$$

(9)

(3) Charging pile position and capacity constraint

$$P_{EV,\text{min}} \leq P_{EV,i} \leq P_{EV,\text{max}} \quad i \in \Omega_{EV}$$

(10)
(4) DG position and capacity constraint

\[ P_{DG,\text{min}} \leq P_{DG,i} \leq P_{DG,\text{max}} \quad i \in \Omega_{DG} \]  \hspace{1cm} (11)

Where \( \Omega_{EV} \) is the collection of node locations allowed to construct charging piles, \( \Omega_{DG} \) is the collection of node locations allowed to construct DG.

3.3. Improved free search algorithm

This program is a double-objective multi-variable nonlinear optimization problem, which cannot be solved by traditional numerical methods, and intelligent algorithms such as genetic algorithm and simulated annealing algorithm may fall into the local optimal solution. Free search algorithm (FSA) is a relatively new swarm intelligence algorithm with strong global search ability and fast convergence speed. In this paper, based on the traditional free search algorithm, double-objective pheromone selection mechanism and adaptive variable step size search mechanism are added to solve the problem that the traditional FSA is not suitable for double-objective optimization and the convergence speed is slow. The algorithm flow chart is as follows.

![Figure 1. The flowchart of improved free search algorithm.](image)

4. Case studies and conclusion

4.1. Space considerations

The example topology of this paper is shown in the figure 2\(^6\)

![Figure 2. A topology of an electrified transportation network.](image)
EV charging piles are generally located near the road, so the alternative nodes for charging pile construction are mainly 2, 3, 4, 5, 6, 19, 20, 21, 26 and 27. 7kW slow charging pile is selected as the planning object, and the number of charging piles at each node is no more than 5. The fixed installation cost of charging piles is 1000USD/set. Based on the scale of the traffic network, the total number of vehicles is determined to be 500, of which electric vehicles account for 20% (100). Photovoltaic and other DG should be connected to the middle and end of the line, and the energy storage, as a supplementary device for intermittent power supply, should be compensated locally at the photovoltaic node. As shown in the figure above, the nodes to be built for photovoltaic power station and energy storage are 16, 17, 18, 24, 25, 31, 32 and 33. The maximum installed capacity of photovoltaic and energy storage is 100kW. The installation price of photovoltaic is 500USD/kW, and the energy storage price is 2000USD/kW.

4.2. Analysis of simulation result
The traffic flow obtained by the traditional optimal path search algorithm and the optimal path algorithm based on the principle of user equilibrium distribution is shown in the figure below.

Through the comparison, traffic flow on congested roads decreases while traffic flow on unblocked roads increases, which is clearly consistent with the practical situation of vehicle travel in a traffic jam in choosing far but not congested routes, so by this algorithm can better simulate the actual traffic situation of transportation network, based on the data of charging pile planning more realistic.

In the double-objective free search algorithm, the target number is 2, the problem dimension is 26, Pareto frontier of optimal configuration is shown in the following figure, and the selected typical planning scheme is shown in Table 1.

| Plan | Number of EV charging pile nodes | DG nodes configure/kW | Economy /USD | Charging satisfaction |
|------|----------------------------------|-----------------------|--------------|----------------------|
| 1    | 2 3 4 5 6 19 20 21 26 27         | 16 17 18 24 25 31 32 33| 550000       | 300                  |
| 2    | 3 4 5 6 19 20 21 26 27          | 17 18 24 25 31 32 33 | 650000       | 800                  |
| 3    | 4 5 6 19 20 21 26 27            | 18 24 25 31 32 33     | 750000       | 1300                 |
| 4    | 5 6 19 20 21 26 27             | 24 25 31 32 33       | 850000       | 1800                 |
| 5    | 6 19 20 21 26 27            | 25 31 32 33         | 950000       | 2300                 |
It can be seen from the results that the Pareto frontier formed by the proposed algorithm has good distribution and can represent all the non-inferior solutions. There is a positive correlation between the user's charging satisfaction and the economic index. Increasing the nodes and number of charging piles can improve the user's charging satisfaction, but it will bring the increase of construction cost and network loss. Increasing the capacity of DG can improve the acceptance capacity of EV charging piles, but it will also bring an increase in economic indicators. In plan 1, the user's charging satisfaction is the highest. The economic cost in plan 2 is the lowest. Plan 3 is the inflection point of the entire Pareto distribution. In this plan economic investment satisfaction is the most obvious. In addition, all the solutions in the solution set are optimal solutions, which can be provided for decision makers as a reference, and the final planning scheme can be decided according to the needs of decision makers.

4.3. Conclusion
Aiming at the problem of location and capacity determination of EV charging piles and DG, this paper takes charging piles and DG as optimization objectives to establish electrified traffic model, and simulates the actual traffic flow based on the principle of user equilibrium distribution. Meanwhile, the uncertainty of DG output is studied to establish a model of DG complementary output. A double-objective optimal programming model with the lowest economic cost and the highest user satisfaction is proposed, and an improved double-objective free search algorithm is used to solve the model. The main conclusions are as follows

1. The traffic network modelled on the principle of user equilibrium distribution can take into account the congestion problem in the actual road. The modelling in this way can better restore the actual payment request of the traffic network and provide reliable data support for charging pile planning.
2. The location and capacity determination of EV charging piles and DG is very important for distribution network planning. Charging piles of EV should be considered at the same time as DG planning.
3. The improved free search algorithm can effectively explore the optimal configuration scheme, and the Pareto frontier made has a good distribution, which can provide a comprehensive scheme choice for decision makers.

Acknowledgments
This work is supported in part by the State Grid Hengshui Electric Supply Company under Grant 5204HS20000J.

References
[1] Wang C.S., Li P. (2010) Development and Challenges of Distributed Generation, the Microgrid and Smart Distribution System. J. Automation of Electric Power Systems, 34(02):10-14+23.
[2] Hu Z.C., Song Y.H., Xu Z.W., et al. (2012) Impacts and Utilization of Electric Vehicles Integration Into Power Systems. J. Transactions of China Electro Technical Society, 32(04):1-10+25.
[3] Wang W.D., Cui X., Ma X., et al. (2015) Multi-Objective Optimal Reactive Power Flow of Distribution Network with Multiple Wind Turbines. J. Power System Technology, 39(07):1860-1865.
[4] Liu Z.P., Wen F.Q., Xue S.Y. et al. (2012) Optimal Siting and Sizing of Electric Vehicle Charging Stations. J. Automation of Electric Power Systems,36(03):54-59.
[5] Liu B.L., Huang X.L., Li J., et al. (2015) Multi-Objective Planning of Distribution Network Containing Distributed Generation and Electric Vehicle Charging Stations. J. Power System Technology, 39(02):450-456.

[6] Kong S.F., Hu Z.J., Xie S.W., et al. (2019) Planning Method of Active Distribution Network Based on Expansion Model of Electrified Traffic Network. J. Power System Technology, 43(11):4160-417