A SOP planning method for distribution network based on improved genetic algorithm considering EV integration

Ziang Li¹ and Lu Zhang*¹

¹College of Information and Electrical Engineering, China Agricultural University, 17 Qinghua East Road, Haidian District, Beijing, 100083, China
E-mail: 1363874730@qq.com (Ziang Li)/ zhanglu1@cau.edu.cn (Lu Zhang)

Abstract. With the progress of electric vehicles, there comes a huge number of problems about cost inflation and workload increases in power distribution systems, which caused by the growing number of electric vehicles plugging. Hence, an optimal planning scheme of soft open point (SOP) considering the connection of electric vehicle to power distribution system is proposed. First of all, a SOP two-layer planning model for site selection and capacity determination was established to seek for site selection and capacity determination, so as to minimize the cost. The hybrid optimization algorithm composed of improved genetic algorithm and power flow algorithm was used to solve the problem. Further, the variation of voltage level, before and after the SOP connected to the distribution network, is also analyzed. Finally, the rationality and feasibility of the two-layer programming model of SOP site selection and constant capacity and the hybrid optimization algorithm composed of improved genetic algorithm and power flow algorithm are analyzed with IEEE 33 node example system, and the planning conclusion of effectively reducing the operating cost of the distribution system is obtained. After plugging in SOP according to the planning results, the node voltage value, the average per unit value and the performance of the distribution system are improved to a certain extent. Meanwhile, the operation efficiency, relative error and the convergence capacity according to the modified algorithm are superior to conventional algorithm.

1. Introduction
At present, China's power distribution network is mainly faced with the challenges of high permeability access of large-scale intermittent distributed generation and a large number of high demands for customized electricity demand [1]. There are many benefits to having a distributed generation connected to a power distribution system [2]. However, due to the randomness and volatility of distributed generation, the power distribution system may have problems such as overvoltage and network blocking [3-4]. With the development of electric vehicles, a large number of electric vehicles are connected to the power distribution system, which will also cause the problem of increasing the load of the power distribution system. SOP plays an important role in improving the power supply reliability and power quality of power distribution network [5]. Wang An used SOP to replace the interconnection switch in the traditional power distribution system, and analyzed and obtained the optimal position of SOP in the access to the power distribution system [6]. Wang Chengshan et al. made a detailed comparative analysis of the optimization effect of SOP and network reconstruction, and verified the advantages and potential benefits of SOP [7]. Liu Jinyuan et al. reduced the load fluctuation in the power distribution system by establishing a distributed energy output and demand response planning model for electric vehicles [8-10]. Shi Wenchao et al. established an opportunity model for making economic decisions in power
distribution systems [11]. At present, the problem of site selection and capacity planning for SOP access to electric vehicle power distribution system has not been involved. This paper proposes a two-layer optimal programming model for power distribution system considering the power electronic equipment access. In order to solve the problem that the genetic algorithm is prone to fall into the local optimum and the convergence rate is not stable under certain conditions [12], we use the hybrid optimization algorithm of the improved genetic algorithm and the power flow algorithm to solve the problem. Finally, we use an IEEE 33 node example system to analyze the rationality and feasibility of the proposed hybrid optimization algorithm, and get the conclusion that the operating cost of the power distribution system can be effectively reduced. At the same time, according to the results after the access to the SOP, we found that the power distribution system in the node voltage value, the average per-unit value and the performance of the power distribution system got a certain level of ascension, it also makes the power distribution system for electric vehicle access to bear ability was strengthened, which increase the given power and reduce the probability of voltage is limited to happen.

2. Power distribution system with SOP access

2.1. System structure composition

Based on the structure of the original traditional power distribution network, the high-power power electronic equipment is used to control and adjust the network parameters of the system, so as to optimize the operation state of the distribution system and tap the operation potential of the system [13].

Figure 1 shows the structure of ac distribution network. This is through the interconnection switch will be connected to the two feeders, so as to constitute the power distribution system.

![Figure 1. Ac distribution network system structure.](image)

The structural framework of ac-dc active distribution system is shown in Figure 2. Line 2 in the ac-dc active distribution network based on SOP has more photovoltaic devices. The main converter station is used to convert an ac line into a dc line. The dc side voltage is 15kV. The function of the slave converter station is to connect the ac and dc lines. The emergence of SOP is to replace the interconnection switch in the traditional power distribution system [14].

![Figure 2. Ac and dc Active Distribution Network system structure connected with SOP.](image)

2.2. Soft open point

The interconnection switch in the power distribution system only has two working states: "off" and "on". However, soft open point (SOP) can realize four-quadrant power control and control the power flow of feeders on both sides of the traditional interconnection switch [15].

Under such operation control mode, the operation of SOP shall satisfy the following constraint conditions (we artificially set the direction of power injection network to be positive): SOP active power constraints

\[
P_{\text{SOP}}^{\text{active}} + P_{\text{SOP}}^{\text{loss}} + P_{\text{SOP}}^{\text{loss}} = 0
\]
\[ P_{\text{Loss}}^{\text{SOP}} = A_{i(j)}^{\text{SOP}} \sqrt{(P_{(i)}^{\text{SOP}})^2 + (Q_{(i)}^{\text{SOP}})^2} \]  

\[ P_{\text{Loss}}^{\text{SOP}} = A_{i(j)}^{\text{SOP}} \sqrt{(P_{(j)}^{\text{SOP}})^2 + (Q_{(j)}^{\text{SOP}})^2} \]  

SOP reactive power constraints:

\[ -\alpha^{(i)} S_{(i)}^{\text{SOP}} \leq Q_{(i)}^{\text{SOP}} \leq \alpha^{(i)} S_{(i)}^{\text{SOP}} \]  

\[ -\alpha^{(j)} S_{(j)}^{\text{SOP}} \leq Q_{(j)}^{\text{SOP}} \leq \alpha^{(j)} S_{(j)}^{\text{SOP}} \]  

SOP capacity constraints:

\[ \sqrt{(P_{(i)}^{\text{SOP}})^2 + (Q_{(i)}^{\text{SOP}})^2} \leq S_{(i)}^{\text{SOP}} \]  

\[ \sqrt{(P_{(j)}^{\text{SOP}})^2 + (Q_{(j)}^{\text{SOP}})^2} \leq S_{(j)}^{\text{SOP}} \]  

In the above formula, \( i \) and \( j \) are the node Numbers connected at both ends of SOP. \( A \) is the loss coefficient of the converter; \( \alpha \) is the reactive power constraint coefficient.

2.3. Stochastic probability model of charging and discharging of electric vehicles

According to the charging and discharging time characteristics and charging and discharging modes of EV, EV can be divided into two types: EV with pure electric load and EV with power distribution system scheduling. The former only absorbs electricity from the power distribution system and does not accept the dispatch of the power distribution system during the peak period. The latter can not only absorb electricity from the power distribution system, but also receive power distribution system dispatch to release power to the power distribution system during the peak period. Therefore, the EV scheduled by the power distribution system is generally charged only during the off-peak period of power supply in the power distribution system \cite{16}. According to the classification method of electric vehicles mentioned above, we can express the charging and discharging power of electric vehicles as follows:

\[ P = P_1 + P_2 \]  

In the above formula, \( P \) is the power absorbed by the electric vehicle from the power distribution system. \( P_1 \) and \( P_2 \) respectively represent the power absorbed from the power distribution system by the electric vehicle with pure electric load and the electric vehicle operated by the power distribution system.

3. SOP site-selection and volumetric two-layer model

3.1. SOP site selection and capacity determination upper layer model

The upper layer model of SOP site selection and fixed capacity is used to find the minimum value of annual power distribution system comprehensive cost. The mathematical expression is as follows:

\[ Z = Z_1 + Z_2 + Z_3 \]  

3.1.1. Annual fixed investment fee \( Z_1 \):

\[ Z_1 = \frac{a^{(1+a)}\gamma}{(1+a)^{\gamma-1}} \sum_{k=1}^{N_{\text{SOP}}} c^{(k)\text{SOP}} S^{(k)\text{SOP}} \]  

In the above formula, \( a \) is the discount rate; \( \gamma \) is the economic service life of SOP; \( N_{\text{SOP}} \) is the number of planned installations of SOP; \( c^{(k)\text{SOP}} \) is the unit capacity investment cost of k SOPs; \( S^{(k)\text{SOP}} \) is the capacity of k SOPs.
3.1.2. Annual operating maintenance cost $Z_2$.

$$Z_2 = \beta \sum_{k=1}^{N_{SOP}} c_{(k)SOP} S_{(k)SOP}$$

(11)

In the above formula, $\beta$ is the annual maintenance cost coefficient of SOP.

3.1.3. Annual power distribution system loss cost $Z_3$.

$$Z_3 = c \cdot t \cdot P_{lose}$$

(12)

In the above formula, $c$ is the unit price of electricity price; $t$ is the power supply time every year; $P_{lose}$ is the active power loss in the power distribution system.

3.2. SOP site selection and capacity determination lower layer model

The SOP site selection and capacity determination lower layer model is an ideal case for minimizing the sum of network loss and SOP loss in the power distribution system. The objective function of the SOP site selection and capacity determination lower layer model is as follows:

$$\min \left\{ \text{days} \sum_{t=1}^{24} \sum_{i=1}^{N} P_{i}^{\text{lose}} - Q_{i}^{\text{lose}} \right\}$$

(13)

In the above equation, $\text{days}$ is 365; $t$ is 24 hours; $P_{i}^{\text{lose}}$ and $Q_{i}^{\text{lose}}$ respectively refer to the active power network loss and reactive power network loss after the system is accessed to SOP.

4. Solution of the SOP site-selection and volumetric two-layer model

In this paper, we study a large-scale mixed integer nonlinear problem, so we use the hybrid optimization algorithm of genetic algorithm and power flow algorithm to solve it. Genetic algorithm as the main framework of the algorithm, the power flow algorithm calculates the active power network loss, and obtains the rated capacity value of the SOP connected to the power distribution system through calculation. The flow chart of the hybrid optimization algorithm is shown in Figure 3.

![Flow chart of hybrid optimization algorithm.](image)

Figure 3. Flow chart of hybrid optimization algorithm.

4.1. Genetic Algorithm

In genetic algorithms, you're dealing with chromosomes, and a certain number of chromosomes make up a population. The idea of genetic algorithm includes five parts: parameter coding, initial population setting, fitness function design, genetic manipulation control and control parameter setting [18].

4.2. The improved genetic algorithm

4.2.1. Optimization of initial population generation. Under certain conditions, the initial population
generated by genetic algorithm has the deficiency of high repetition rate or not wide coverage [19]. Therefore, we introduce the concept of cost speed ratio to solve the problem. Cost speed ratio, that is, the ratio of the increase in the running speed of the algorithm to the increase in the required cost. When generating the initial solution, first select one third of the initial solution as each task node, and then select a ratio between the amount of time reduction and the amount of cost increase. At the same time, select the scheme with a smaller ratio of cost speed. Finally, generate the initial solution one by one according to the order of task nodes to complete the optimization of the initial population.

4.2.2. Optimization of individual selection method. In genetic algorithm, roulette wheel selection is commonly used for individual selection. However, roulette wheel selection cannot guarantee the diversity of species within the population. Therefore, we introduce a roulette wheel selection based on Hamming distance. Hamming distance is used in error control coding during data transmission. In the improved genetic algorithm, Hamming distance is used to measure the population diversity before and after individual selection.

The calculation formula of the average Hamming distance of the individual population is:

\[
\bar{h} = \frac{2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} h(C_i, C_j)}{N(N-1)} \quad (14)
\]

In the above equation, \(N\) is the initial population size, and \(h(C_i, C_j)\) is the Hamming distance between individual \(C_i\) and \(C_j\).

4.2.3. Optimization of crossover operators. Because the crossover probability in the genetic algorithm is constant, the global search ability of the algorithm will be affected to some extent [20]. In order to enhance the searching ability of the algorithm, we change the crossover probability from the original constant to the following formula:

\[
P_c = \begin{cases} 
P_{\text{max}} e^{-\frac{i}{N}}, & P_{\text{max}} e^{-\frac{i}{N}} < P_{\text{min}} \\ 
P_{\text{max}}, & \text{other} \\ \end{cases} \quad (15)
\]

In the above formula, \(i\) is the number of iterations, \(N\) is the upper limit of the number of iterations, \(P_{\text{max}}\) is the preset maximum crossover probability, and \(P_{\text{min}}\) is the preset minimum crossover probability.

4.3. Power flow algorithm

We can use the power flow algorithm to work out a safe, efficient and operational requirements of the power distribution system optimization planning scheme. The relationship between node voltage and node current is shown in the following formula:

\[
I_n = YV_n \quad (16)
\]

The relationship between node current and node power is as follows:

\[
I_n = \frac{P_n - jQ_n}{V_n} (i = 1, 2, 3, \ldots, n) \quad (17)
\]

The complex voltage variables in the electric system can be represented by the following polar coordinates:

\[
V_{(i)} = e^j + jf_{(i)} \quad (18)
\]

Complex admittance is shown in the following formula:

\[
Y_{(ij)} = G_{(ij)} + jB_{(ij)} \quad (19)
\]

The power flow equation in the form of rectangular coordinates is as follows:
\[ P(i) = e(i) \sum_{j \in i} (G(ij)e(j) - B(ij)f(j)) + f(i) \sum_{j \in i} (G(ij)f(j) + B(ij)e(j)) \quad (i = 1, 2, 3, \ldots, n) \quad (20) \]
\[ Q(i) = f(i) \sum_{j \in i} (G(ij)e(j) - B(ij)f(j)) - e(i) \sum_{j \in i} (G(ij)f(j) + B(ij)e(j)) \quad (i = 1, 2, 3, \ldots, n) \quad (21) \]

5. Interpretation of result

In this paper, IEEE 33 node example system is used to verify the programming model and hybrid optimization algorithm. The structure diagram of IEEE 33 node example system is shown in Figure 4.

![Figure 4. The structure of the IEEE 33 node example system.](image)

The parameter values used in the example are shown in Table 1.

| Parametric variable                  | Value   |
|--------------------------------------|---------|
| \( \alpha \): Discount rate          | 0.10    |
| \( \gamma \): Economic life of SOP   | 30      |
| \( c_{SO} \): SOP unit capacity investment cost (yuan/kVA) | 1000    |
| The SOP unit optimizes capacity (kVA) | 200     |
| Loss coefficient of SOP              | 0.01    |
| \( \beta \): SOP operation and maintenance cost coefficient | 0.01    |

The hybrid optimization algorithm was implemented by MATLAB script program. The hardware environment of the test system was Inter Core i7, 1.80GHz dual-core. 8 GB of memory; We use a 256G hard disk PC computer, the operating system we use is Win10 64bit, and the development environment we use is MATLAB R2018a.

According to the electricity price of most regions in China published by State Grid Corporation of China, the load time-of-use electricity price used in this study is shown in Table 2.

| Peak/Valley | Peak period | Normal period | Valley period |
|-------------|-------------|---------------|--------------|
| Time quantum| 10: 00-15:00 | 07: 00-10:00 | 00: 00-07:00 |
| 00: 00-07:00 | 00: 00-24:00 |
| Price (yuan/kW-h) | 0.8 | 0.6 | 0.3 |

According to literature [17], we obtained the market share ratio of different types of electric vehicles and the charging and discharging period of each type of electric vehicle, as shown in Table 3.
Table 3. The proportion of electric vehicles and the charging and discharging period.

| Detailed classification                  | Proportion | Charging time                | Discharging time |
|------------------------------------------|------------|------------------------------|------------------|
| EV with pure electricity                 |            |                              |                  |
| Public electric vehicle                  | 20%        | 20:00-7:00                   | —                |
| Private electric vehicle                 | 40%        | 10:00-16:00; 20:00-7:00      | —                |
| EV with power distribution system        |            |                              |                  |
| Dispatchable electric vehicles           | 20%        | 22:00-7:00; 20:00-23:00      | 10:00-16:00; 00  |

We assume that the charging and discharging power of all EVs is 3.6kw, and its charging rate is 0.4. The available discharge energy efficiency of the EV with power distribution system scheduling is 0.7.

5.1. Planning results and cost analysis

The SOP planning results calculated by the hybrid optimization algorithm and the budget cost analysis results before and after SOP access are shown in Table 4.

Table 4. Planning results and cost analysis.

| Installation site | TS1  | TS2  | TS3  | TS4  | TS5  | Planning before |
|-------------------|------|------|------|------|------|-----------------|
| Number of installations | 10   | 9    | 5    | 4    | 6    | 0               |
| The capacity of the SOP | 1000kVA | 900 kVA | 500 kVA | 400 kVA | 600 kVA | 0               |
| Z1(ten thousand yuan) | 20   | 18   | 10   | 8    | 12   | —               |
| Z2(ten thousand yuan) | 14.68| 13.23| 6.11 | 3.85 | 10.29| —               |
| Z3(ten thousand yuan) | 1161.40| 1158.04| 1168.39| 1168.62| 1168.46| 1232.83         |
| Z (ten thousand yuan) | 1196.08| 1189.27| 1184.50| 1180.47| 1190.75| 1232.83         |

We can find that the installation of SOP at location TS2 has a better effect on network loss reduction, but the cost is high. Considering the lowest total cost, we found that it was suitable to install SOP at location TS4. Considering various considerations, we believe that the optimal situation is to access the SOP with a capacity of 400kVA to location TS4 in the power distribution system. After the optimal planning location and planning capacity are adopted, the annual comprehensive cost before the planning is reduced by about 480,000 yuan, with a decrease rate of 4.25%. In addition to economic benefits, SOP can also improve the absorption capacity of distributed generation.

5.2. Analysis of the influence of SOP on power distribution system

In this section, the variation of node voltage value before and after SOP is connected to the IEEE 33 node example system is analyzed. We take the standard voltage value of each node to be 12.66kV. The analysis results are shown in Table 5.

Table 5. Analysis of voltage values of nodes before and after SOP access.

| Average nodal voltage | Per-unit value |
|-----------------------|----------------|
| Before                | 11.0348        | 0.8716         |
| After                 | 11.6285        | 0.9185         |

As we can see, with the access of SOP, the overall performance of the power distribution system has been increased to a certain extent. After the planning, the bearing capacity of the power distribution system for electric vehicles has also been improved, and the absorption energy of electric vehicles has been strengthened, so as to reduce the probability of voltage over-limit to a certain extent.
5.3. Comparative analysis before and after model solving algorithm improvement

The following text will compare and analyze the two different algorithms before and after the application of the same problem. We compared and analyzed the improved algorithms from the aspects of operating efficiency, error analysis and performance comparison.

![Figure 5. Operating efficiency comparison diagram.](image)

![Figure 6. Relative error comparison graph.](image)

![Figure 7. Comparison diagram of convergence rate.](image)

It can be found from Figure 5 that the increase trend of scheduling cost of the improved algorithm is significantly lower than that of the improved algorithm as the number of task nodes increases. This also reflects that the improved algorithm has been significantly improved in operation efficiency.

According to Figure 6, we find that the improved algorithm has higher accuracy. This means that the results obtained by the optimized algorithm are more reliable and better.

According to Figure 7, we can find that the optimized algorithm has stronger convergence ability, better performance and faster search for the optimal solution.

6. Conclusion

In the process of research, we decompose the large-scale mixed integer nonlinear programming problem and solve the problem by using the hybrid optimization algorithm. This method guarantees the efficiency of the process and the reliability of the results. The verification results of IEEE33 node example system show that the planned power distribution system can have better network loss reduction capacity, and at the same time, the annual comprehensive cost will be reduced by about 4.25%. The node voltage value, the average per-unit value and the performance of the power distribution system are improved to a certain extent, which makes the power distribution system to the electric vehicle access capacity to strengthen, thus increasing the absorption capacity, reduce the probability of voltage out of limit.

When solving the optimal programming scheme of SOP, we optimized the initial population generated in the genetic algorithm, and used the improved individual selection method and crossover operator to alleviate the defects caused by the poor fitness of the initial population and good fitness of the later population that were not taken into account in the original genetic algorithm. After verification, we find that the improved algorithm has stronger global search ability, more stable convergence ability, stronger operation efficiency and higher result accuracy.

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