A Multilayer Path Planning Method for High Voltage Distribution Network Based on the Floyd-Warshall Algorithm

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Abstract. With the development of the city, a huge number of distribution networks are waiting for planning. A reasonable planning scheme can meet the power demand and reduce the investment cost. In this paper, a life cycle cost model including the investments of substation and wiring is established with the constraints about load flow calculation and maximum load of wiring. Additionally, a multilayer planning method based on the Floyd-Warshall algorithm has been proposed to solve the model. The area of the city containing substations is divided based on the position of load through the hybrid clusters algorithm in the method. Then, using the divided result of power supply area, the cost matrix for the multilayer path planning method can be constructed through the principle of the method. Lastly, with the cost matrix, the planning scheme in each area will be provided by the Floyd-Warshall algorithm. The result on the actual planning area between the two algorithms shows the total cost of the investment is decreased through using the planning method in this paper.

1. Introduction

The distribution network connects between the power transmission network and users as a bridge, which was essential in the power grid to ensure power transmit from the grid to the low voltage network [1]. With the pressure of development, plenty of new urban planning caused a huge number of distribution networks were waiting to be planned. The planning problem of distribution was a highly complex system planning problem that including forecast and calculates the load, determines the capacity and location of the sub-station, and design the wiring connection under the constrained condition [2,3]. A reasonable distribution network planning scheme can satisfy the demand for power in a region and decrease the cost of investment of society for a long time [4].

To solve the problem of distribution network planning, various innovation models and methods had been proposed. Geographic and load information were the first condition that needs to be considered in the planning model. Usually, the geographic information such as route in city or barrier in the wilderness can be abstracted by graph theory [5], while the weight of the path in the graph should consider the real situation in the urban area like reusable corridors and existing conduit structuring [6].

The results of power supply area division can influence the planning situation to some extent, and therefore, the principle of dividing supply area should not base on average distribution, national policy or administrative division but aim to minimize the investment [7,8]. The load situation also should be considered when divided the supply area, and some methods that complemented the load characteristic to decrease the investment of equipment in the distribution network were introduced [9,10]. It can improve the economy of the distribution network, but reliability was more important than economic in realistic planning. Once the load had changed, it may affect the stability and safety of the power grid.
Cluster algorithm had been used to make the decision for choosing the site with considered load distribution in MV distribution network [11], but it is not satisfied the demand of high voltage (HV) distribution network. Geographic information can provide a significant criterion for planning problems that make problem can be solved with various algorithms after simplification, simultaneously [5,12-14]. The planning result may divorce from reality without geographic information [15].

Some intelligent algorithms were used to solve complex problems in all walks of life including the planning problem in distribution network unexceptionally [5,15,16,17]. Different from dynamic programming algorithms such as the Floyd-Warshall algorithm [18], it was easily made the result fell into the local optimal value in the meantime. To solve this problem, a hybrid clusters algorithm is proposed in this paper. According to this algorithm, some adverse effects that come from the disadvantage of the clustering algorithm can be reduced and the algorithm can describe the data in the planning area with more accuracy. Subsequently, a method for multilayer planning based on the Floyd-Warshall algorithm, which can plan the different typical wiring connection schemes with a multilayer map, will be established.

2. Methodology

2.1. Framework of the HV distribution network planning

The framework of the HV distribution network planning was illustrated in Figure 1. It started with spatial load forecasting, which was what most planning problems need to deal with. Then the power supply area should be divided for subsequent work. After that, the framework was divided into two parts, those were the substation planning part and the wiring planning part, which needed to be discussed in this methodology. The substation planning part proceeded from the substation classification to model calculation, and the wiring planning part aimed to generate the path weight, which could express the correlation between the different substations correctly, through calculating the wiring model. Subsequently, a life cycle cost model was established with information of two parts that could be used to generate the matrix. Finally, the model could be solved by the Floyd-Warshall algorithm in each area.

2.2. Planning model of HV distribution network

The planning model of the HV distribution network given by Equation (1) had been mainly divided into two parts.

\[
\min C^{co} = \sum_{i \in N} (C^{TS}_i + C^{CW}_i) 
\]

where \( C^{co} \) represented the total cost of the planning model; \( N \) was the number of supply areas; \( C^{TS}_i \) represented the cost of wiring and \( C^{CW}_i \) represented the substation in each supply areas.

Considering the real conditions, there was still a large proportion of other costs when the construction cost had been subtracted. To reflect the economy more accurately, a life cycle cost model should be
taken into consideration to reduce the deviation between planning cost and actual cost. In the substation part of planning, the main objective was to establish the cost model of substation as realistically as possible. For that reason, the substation part of the planning model which was incorporated with construction cost, operation cost and recovery cost was expressed as Equation (2).

$$C_{TS}^i = I_{TS}^i + \sum_{n \in T} \sum_{n \in N_{TS}} ((1 + r)^t (C_{TS}^{i n, L} + C_{TS}^{i n, O} + C_{TS}^{i n, M}) + (1 + r)^{-\tau})$$

where $I_{TS}^i$ represented the investment of substation; $T$ represented the set of the year of planning horizon; $N_{TS}$ was the number of transformer substation; $r$ represented the rate of interest; $C_{TS}^{i n, L}$, $C_{TS}^{i n, O}$ and $C_{TS}^{i n, M}$ were parts of operation cost and represent loss cost of substation, overhaul cost of substation and malfunction cost of substation respectively. $\tau$ was a constant value of years that depends on designed life from construction to demolition. $C_{i,n,D}$ represented the recovery cost.

Similar to the substation part, a life cycle cost model had been established as Equation (3) to obtain a more accurate result, especially in the distribution network planning problem.

$$C_{W}^i = I_{W}^i + \sum_{n \in T} \sum_{n \in N_{W}} (1 + r)^t (C_{W}^{i n, L} + C_{W}^{i n, O} + C_{W}^{i n, M})$$

The structural difference between the wiring part and substation part of the planning model was reflected in the wiring was not worthy of recycling like transformers in the substation, when it was broken or reach the end of life. That was the reason why Equation (3) has not the item about recovery cost. In this equation, $I_{W}^i$ represents the investment of wiring; $N_{W}$ was the number of sets of typical wiring connection; $C_{W}^{i n, L}$, $C_{W}^{i n, O}$ and $C_{W}^{i n, M}$ were also both part of operation cost and represent loss cost of wiring, overhaul cost of wiring and malfunction cost of wiring respectively.

In addition, the planning model of HV distribution network should be constrained with Equation (4).

$$f(TYP') = 0$$
$$g(TYP') \leq 0$$
$$P_m \leq P_{n,max} \quad m \in N_W$$

where the function $f(TYP')$ was the equality constraints of load flow calculation; function $g(TYP')$ was the inequality constraints of load flow calculation; $P_m$ and $P_{n,max}$ were the load of wiring $m$ and the maximum load of wiring $m$ respectively.

3. Multilayer path planning method for HV distribution network

3.1. Hybrid clusters algorithm for HV distribution network

The hybrid clusters algorithm was a combination of two clustering algorithms, which were the DBSCAN and the K-means algorithm, that could describe the density distribution of samples and abided by the minimum error criterion to assign data respectively. The algorithm of DBSCAN could use a set of neighborhood parameters $\varepsilon$ and $MinPts$ to describe the density distribution. $\varepsilon$ represented the radius of neighborhoods; $MinPts$ represented the minimum size of the sample in the neighborhood.

The algorithm of K-means that could try to get the minimum error criterion works as follows.

$$d = \sum_{i=1}^{k} \sum_{x \in CS} \left| x - \frac{1}{|CS|} \sum_{x \in CS} x \right|^2$$

where $k$ represented the number of clusters; the $CS$ represented the set of samples. Equation (5) could be used to minimize the sum of the distance between each sample and average vector with the quantitative constraint of parameter $k$ by iterative method. Different values of $k$ would cause different results, for that reason, the initialization of $k$ and the average vector should be constrained by DBSCAN, in the hybrid clusters algorithm. The parameters $k$ and the average vectors depended on the number and the center coordinates which calculated in Equation (6) respectively of the power supply area generated by DBSCAN.
\[ v = \sum_{i=1}^{k} \frac{\sum_{x \in CS} xP_x}{\sum_{x \in CS} P_x} \]  

(6)

where \( v \) represented the average vector; \( P_x \) represented the load of each sample. The advantage of the method, which used the load torque to calculate the average vectors, was the uneven distribution of heavy loads had been considered to increase the reasonable substation classification in each power supply area. By the change of average vectors, equation (5) should be rewritten as follows:

\[ d = \sum_{i=1}^{k} \sum_{x \in CS} \left| x - \frac{\sum_{x \in CS} xP_x}{\sum_{x \in CS} P_x} \right| \]  

(7)

In the urban area, the distribution of load had strong density characteristics that could be used for the DBSCAN algorithm to obtain the supply area of the city. This algorithm could get a good result in load clustering, but could not classify the substation site that waiting to be selected. Through hybridize the DBSCAN and \( K \)-means, two algorithms could accomplish the objective of substation part with the complementarity of each other.

3.2. Multilayer path planning method based Floyd-Warshall algorithm

Floyd-Warshall was an algorithm based on dynamic programming to solve the all-pairs shortest paths (APSP) problem, that is, found the shortest path between multiple points with the weighted graph. The cost of civil engineering usually accounted for a large proportion of the wiring part when considering the real situation, and the planning method should consider the minimum of the cost rather than the shortest length of the path. Thus, reused the cable conduit that had been already constructed was a major method to reduce the cost.

Multilayer path planning method that based Floyd-Warshall algorithm, in this paper, was an extension of Floyd-Warshall algorithm, which illustrated in Figure 2, to satisfy the requirements of HV distribution network planning.

In Figure 2, there was a three-layer structure as an example to explain the method. The left part was entire structure with connection path between different layer, the right part was same structure with shortest path. All the layers described a same situation of the planning area, once any path weight had been changed, all of layers would been change at same time. According to this structure, some points such as \( T_1 \) and \( T_4 \) as necessary points had been added to the solving process to calculate the shortest path between \( S_1 \) and \( S_4 \). The principle of method was shown in Equation (8)-(11).

\[ M_{Cost} = M_R \otimes M_p + I \otimes (M_p \ast M_{CV}) + M_{CT} \]  

(8)

\[ M_R = \begin{bmatrix} m_1 & 0 & \text{inf} \\ 0 & m_2 & 0 \\ \text{inf} & 0 & m_3 \end{bmatrix} \]  

(9)

\[ M_p \ast M_{CV} = [l_{(i,j)}]_{x=0} \ast [p_{CV(i,j)}]_{x=0} \]  

(10)
where $M_{cost}$ represented the cost matrix that to be used by Floyd-Warshall algorithm; $M_r$ represented the matrix with the relationship of multilayer and price of different cable types; $I$ represented the identity matrix; $M_{cv}$ was a matrix that represented cost of civil engineering, which would change the value after finished one wiring connection; $M_{ct}$ represented cost of transformer substation and the elements $C_{ij}$ in matrix represented the connection situation between two layers; Operational character $\otimes$ and $*$ represented the Kronecker Product and Hadamard Product respectively. Through the Kronecker Product, the matrix $M_r$, which included the information of price in each layer, would be expanded to a $3n$ orders of matrix. With the matrix $M_{cost}$ in which all the elements in the planning model of HV distribution network had been included, that is, the minimum cost of planning problem could be solved through the Floyd-Warshall algorithm.

4. Case Study
In this section, a real urban area in China to be planned was used to be an example of the demonstration of the planning method in this paper. The map of the load area was illustrated in Figure 3.

The overall load of the area was 1130.042 MVA. With the clustered of the load by used the hybrid clusters algorithm in Figure 4, the load in clusters was 1121.391 MVA that accounts for 99.23% because of the feature of DBSCAN. So, the load which had not cluster could be considered to have no influence on the results. To satisfy the demand of each supply area, the optimal solution of substation for the area was shown in Table 1.

| Area | Load (MVA) | Demand (MAV) | Result (MVA) | Average load rate |
|------|------------|--------------|--------------|-------------------|
| 1    | 147.322    | 294.644      | 3×(50×2)     | 49.11%            |
| 2    | 210.837    | 421.674      | 2×(63+50)+2×(50×2) | 49.49%            |
| 3    | 202.234    | 404.268      | 1×(63+50)+3×(50×2) | 48.97%            |
| 4    | 380.161    | 760.322      | 5×(63+50)+2×(50×2) | 49.69%            |
| 5    | 74.562     | 149.124      | 2×(50×2)     | 37.28%            |
| 6    | 106.374    | 212.748      | 1×(63+50)+1×(50×2) | 49.94%            |
To ensure the reliability of the power supply, a scheme of two-sided power was preferred. And remaining substations adopt the single-side scheme.

The contrast between two connective results of planning in this area with the method in this paper and method of shortest path respectively was illustrated in Figure 5 and Figure 6, and the results of data shown in Table 2.

Table 2. The contrast results between two planning method.

| Area | Multilayer path planning method | | Shortest path planning method | | Cost variance |
|------|-------------------------------|----------------|-----------------------------|----------------|----------------|
|      | Length (km) | Cost (million CNY) | Length (km) | Cost (million CNY) | (million CNY) |
| 1    | 4.19 | 146.21 | 4.19 | 146.21 | 2.12 |
| 2    | 2.04 | 70.15 | 1.95 | 72.27 | 7.94 |
| 3    | 6.82 | 205.61 | 6.82 | 205.61 | 7.39 |
| 4    | 7.39 | 196.57 | 7.33 | 204.51 | 6.76 |
| 5    | 5.86 | 182.56 | 5.86 | 182.56 | 7.10 |
| 6    | 7.47 | 194.02 | 7.10 | 200.78 | 6.76 |
| 7    | 7.44 | 264.70 | 7.44 | 264.70 | 7.64 |
| 8    | 7.64 | 248.91 | 7.64 | 248.91 | -2.08 |
| 9    | 7.76 | 250.91 | 7.76 | 250.91 | 81.03 |
| 10   | 1.30 | 83.11 | 1.30 | 83.11 | 0.00 |
| 11   | 8.70 | 167.01 | 8.31 | 176.52 | 9.51 |
| 12   | 6.67 | 170.45 | 6.67 | 170.45 | 0.00 |

From the comparison result of both methods, the shortest path planning method aimed to choose the shortest path for each wiring to be planed as usual, but the multilayer path planning method chose the path considering the total cost of the investment rather than chose the shortest path as planning scheme. It would tend to use the tunnel, which had been already established for the pipeline. By using the method in this paper, the total cost of the investment could be reduced 24.26 million CNY.

5. Conclusions

In this paper, the power supply area and substation were divided by the hybrid clustering algorithm. And the multi-layer path planning method based on dynamic programming was used to solve the life cycle cost model. It provided a new way for distribution network planning under complex urban road conditions. The method was verified in an actual area. The comparisons between the proposed method and the traditional shortest path planning method show that the proposed method was more economic. This method still had some imperfections, such as the medium voltage distribution network and new energy resources system had not been considered. Those would be solved in the following research.
References

[1] Kazmi, S.A.A.; Shahzad, M.K.; Shin, D.R. (2017) Multi-Objective Planning Techniques in Distribution Networks: A Composite Review. Energies, 10:208.

[2] Vahidinasab, V.; Tabarzadi, M.; Arasteh, H.; Alizadeh, M.I.; Beigi, M.M.; Sheikhzadeh, H.R.; Mehran, K.; Sepasian, M.S. (2020) Overview of Electric Energy Distribution Networks Expansion Planning. IEEE Access, 8:34750-34769.

[3] Nahman, J.M.; Peric, D.M. (2008) Optimal Planning of Radial Distribution Networks by Simulated Annealing Technique. IEEE Transactions on Power Systems. 23:790-795.

[4] Farhangi, H. (2010) The path of the smart grid. IEEE Power Energy Mag. 18–28.

[5] Wang, Z.; Lin, D.; Zeng, G.; Yu, T. (2020) A Practical Large-Scale Distribution Network Planning Model Based on Elite Ant-Q. IEEE Access. 8:58912-58922.

[6] Li, Z.; Wu, W.; Zhang, B.; Tai, X. (2020) Feeder-corridor-based distribution network planning model with explicit reliability constraints. IET Gener. Transm. Distrib. 14:5310-5318.

[7] Li, L.; Xie, Y.; He, L.; Ge, H.; Wu, D. (2018) Research on substation planning of distribution network with microgrid. In: IOP Conference Series-Earth and Environmental Science, 2018 4th International Conference on Environmental Science and Material Application. Xian, PEOPLE S R CHINA. 032025, 252.

[8] Sun, K.; He, D.; Wang, L.; Wang, H.; Pan, H.; Sun, Z. (2018) A Grid-Based Method for Distribution Network Planning in Urban Areas. In: IOP Conference Series-Earth and Environmental Science, 2018 First International Conference on Environment Prevention and Pollution Control Technology, Tokyo Univ Sci. Tokyo, JAPAN. 052053, 199.

[9] Liu, W.; Liu, H.; Wang, F.; Wang, C. Zhao, L.; Wang, H. (2020) Practical Automatic Planning for MV Distribution Network Considering Complementation of Load Characteristic and Power Supply Unit Partitioning. IEEE Access. 8:91807-91817.

[10] Alarcon, J.A.; Santamaria, F.; Al-Sumaiti, A.S.; Rivera, S. (2020) Low-Capacity Exploitation of Distribution Networks and Its Effect on the Planning of Distribution Networks. Energies. 13:1920.

[11] Li, Y.; Du, M.; Xie, W.; Yang, B.; Fang, C.; Zhang, Y.; Wang, S. (2018) Method for division of urban load power supply district based on cluster analysis. IET Gener. Transm. Distrib. 12:4577-4581.

[12] Valenzuela, A.; Inga, E.; Simani, S. (2019) Planning of a Resilient Underground Distribution Network Using Georeferenced Data. Energies. 12:644.

[13] Valenzuela, A.; Montalvo, I.; Inga, E. (2019) A Decision-Making Tool for Electric Distribution Network Planning Based on Heuristics and Georeferenced Data. Energies. 12:4065.

[14] Li, Z.; Wu, W.; Zhang, B.; Tai, X. (2020) Hexagon raster-based method for distribution network planning considering line routes and pole locations. IET Gener. Transm. Distrib. 14:1420-1429.

[15] Wu, K.; Li, K.; Liang, R.; Ma, R.; Zhao, Y.; Wang, J.; Qi, L.; Liu, S.; Han, C.; Yang, L.; Huang, M. (2018) A Joint Planning Method for Substations and Lines in Distribution Systems Based on the Parallel Bird Swarm Algorithm. Energies. 11:2669.

[16] Ahmadian, A.; Elkamel, A.; Mazouz, A. (2019) An Improved Hybrid Particle Swarm Optimization and Tabu Search Algorithm for Expansion Planning of Large Dimension Electric Distribution Network. Energies. 12:3052.

[17] Nahman, J.; Peric, D. (2008) Optimal planning of radial distribution networks by simulated annealing technique. IEEE Transactions on Power Systems 23:790-795.

[18] Risald.; Mirino, A.; Suyoto. (2017) Best Routes Selection Using Dijkstra And Floyd-Warshall Algorithm. International Conference on Information & Communication Technology and Systems, 11th International Conference on Information and Communication Technology and System. Surabaya, INDONESIA. 155-158.