A NEW DISTRIBUTION SUBSTATION MULTI-STAGE PLANNING ALGORITHM BASED ON DYNAMIC PROGRAMMING

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ABSTRACT

This paper proposes a new model for solving sitting, sizing, timing and defining the associated service area of distribution substation multi-stage optimization planning. In this model, the method of Dynamic programming is applied to solve the problem. Firstly, the optimization of substation in the target year is performed. Secondly, the method takes into account some heuristic rules to reduce the dimension of the problem and provide the overall optimal planning solution of distribution substation. The proposed model is applied to a practical case and the results demonstrate the method is practicable.

Keywords : Distribution substation; multi-stage; Dynamic programming; heuristic rules

1. INTRODUCTION

Recently, there has been a noticeable progress in the research on substation planning and a variety of models and algorithms have been developed [1][2]. However, the limitations still exist:

1) The possibilities of voltage and capacity upgrades of substation were not considered in the models of continuous location selection of either single or multiple power sources. Therefore, the existing models cannot be applied to an ongoing distribution planning.

2) In general, planning of distribution reconstruction is a long-term process and should be divided into several stages. It not only needs to determine the final planning solution in the target year, but also will provide reasonable planning procedure among the middle years. Almost all of the existing models primarily focus on single-stage planning and are hardly able to cope with multiple-stage optimization.

The dynamic programming is an effective solution, which provides theory and method to research into the multi-stage decision problems [3][4]. The establishment of the dynamic programming mathematical model generally includes the following steps: dividing stages, determining the state variables, decision variables and their value ranges, establishing the state transition equation, determining the stage effects and the optimal index function.

In this paper, the optimization of substation in the target year is performed, which indicates all the equipment that will be constructed during the period of the planning study.

Secondly, the planning among the middle years will be divided into several stages and the optimal decision of substation locations and capacity in the target year are the candidates in middle year planning respectively. A model of dynamic programming is established and heuristic algorithm is used to reduce the dimension of the problem. In each stage, the solution includes the location of substations should be built, the capacities and the covered areas of power supply, and so on.. In comparison of the uncertain objective multi-stage substation planning, the proposed method is more reasonable and practical for engineering application.

The proposed model is applied to a practical case and the results demonstrate that the method is useful in the domain.

2. MODEL DESCRIPTION

2.1 Model analysis

The Multi-stage distribution planning problem could be illustrated from the perspective of graph theory[5]. The states is defined as the vertices. The transfer between the two states is defined as the edge and the incremental value in the transfer process is defined as the edge weights. So a directed acyclic weighted graph is composed as shown in Fig.1.

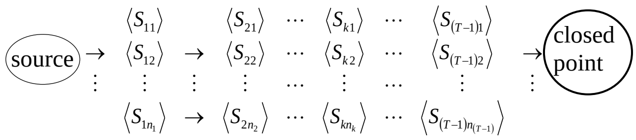


Fig.1. Dynamic programming network diagram

2.2 Model process

The model is built following the steps of Dynamic programming method:

(1)Stage division: either the time or the number of substation candidates could be used as the stage parameter, but the former one conforms to the actual work requirements. In this paper, the number of stages is needed to adopt a bigger one for some planning area with rapid load growth.

Stage variables is as shown in Fig.1, D_k indicates stage k, k=1,2,$\cdots$,T, T is the number of stages.

(2)Model states: D_k is a combination of the two state variables. One is the state of the substation, and the other is the capacity state. The former variable indicates a collection of the substations which are put into from the beginning to stage D_k and the original ones, while the latter one indicates a collection of all the new substation capacity type until D_k and the original ones.

State variables is as shown in Fig.1, where $S_{k,j}$ is state j in D_k.

$$S_{k,j} = \{X_i\},\quad i=0,1,2,\cdots,k,\quad j=1,2,\cdots,n_k \tag{1}$$

Where n_k is the number of states in D_k, X_0 is a collection of the original substations and their capacities, $X_1,X_2,\ldots,X_k$, respectively, is the collection of the new substations and their capacities in $D_1,D_2,\ldots D_k$.

If S_k is the possible state set in D_k, then state j must meet the condition: $S_{k,j}\in S_k$.

(3) Decision variables: decision variable is a combination of the two decision variables, i.e. substations and capacities. $u(S_{k,j})$ indicates the combination decision variables of the new substations and their capacities at state j in D_k, such as $u(S_{k,j})=S_{k+1,i}$, which indicates the decision-making that the state transfer to state i in D_{k+1}. If $u(S_k)$ is a possible decision set in D_k, then the decision-making at state j in D_k must meet the condition: $u(S_{k,j}) \in u(S_k)$.

(4) State transition equation: it means a change process from one state to another, that is, if the state variable S_k and the decision variable $u(S_k)$ in D_k are given, then the state variable S_{k+1} is determined subsequently, which is denoted by: $S_{k+1}=T_k(S_k,u(S_k))$

(5)Strategy: the sequences of decision-making function which consist of each stage decision $u(S_k)$ ($k = 1,2,\ldots,T$) in the substation planning, constitutes a strategy, denoted by $P_{1,T}(S_1)$.

$$P_{1,T}(S_1)=\{u(S_1), u(S_2),\ldots, u(S_T)\}$$

(6) Index function: in terms of the problem in this paper, it is necessary to consider both stable and operational investments of the substations and lines in the whole planning period. The index function of the dynamic programming model is as follows:

$$C = \min(Cost_{substation} + Cost_{Line})$$

Where,

$$Cost_{substation} = \sum_{k=1}^{T}\sum_{i=1}^{N}\left\{ f_1(S_i,k)\left[\frac{r_0(1+r_0)^{ms}}{(1+r_0)^{ms}-1}\right] + u(S_i,k)\right\}\frac{1}{(1+r)^{y(k)}}$$

$$Cost_{Line} = \alpha\sum_{k=1}^{T}\sum_{i=1}^{N}\sum_{j\in J_i(k)}\left\{W_j^2(k)\eta d_{ij} + \beta\left[\frac{r_0(1+r_0)^{ml}}{(1+r_0)^{ml}-1}\right]\eta d_{ij}\right\}\frac{1}{(1+\mathrm{r})^{y(k)}}$$

$$\alpha = \frac{\alpha_1\times\alpha_2\times\alpha_3}{U^2\times\cos^2\varphi}$$

Subject to:

$$\sum_{j\in J_i(k)} W_j(k) \le S_i(k) e(S_i(k))\cos\varphi,\quad i=1,2,\ldots,N \tag{2}$$

Where, $Cost_{substation}$ is the total cost, which consists of the fixed cost with the time value for substations and estimated annual operating and maintenance costs; $Cost_{Line}$ is the investment of the substation secondary lines taking into account the time value and the estimated cost of loss for every year.

Where N is the total number of substations (including existing and ones to be built); $S_i(k)$ is the capacity of substation i in stage k; $J_i(k)$ is the collection of the load points that substation i supplies in stage k; $e(S_i(k))$ is the load rate of substation i in stage k; $\cos\varphi$ is the power factor; ml is the depreciation period of the substation secondary side lines; ms is the depreciation period of the substation; r_0 is the investment recovery rate; r is the discount rate; $f_1(S_i,k)$ is the investment of substation i taking into account the land costs in stage k, in which the cost of the existing substations is zero; $u(S_i,k)$ is the annual operational costs of substation i in stage k; $y(k)$ is the initial year number of stage k; $W_j(k)$ is the value of the load j forecast in stage k; d_{ij} is the Euclidean distance between substation i and load j; η is the terrain complex factor; α is the approximate conversion factor of the network loss; α_1 is the price; α_2 is the resistance per unit length of the secondary lines; α_3 is hours that wear and tear for each year; U is the line voltage of the secondary lines; s is the per unit length costs for secondary lines; T is the total number of the planning stage.

3. MODEL CALCULATION

3.1 Dimension reduction methods and heuristic rules

If there are m states in stage k, the number of decision variables is n in each stage, then,

$$m = n^k$$

From the above formula, the number of states at each stage increase significantly with the increment of stage variable k and decision variable n, which may cause the calculation more complicated. There are two ways to reduce the number of states, to reduce the number of stages, or to reduce n value. The latter can reduce the number of the total states or the states in each stage.

Several heuristic rules are proposed to remove the decision variables that have smaller possibility to generate the optimal solution and improve the calculation efficiency.

(1)Substation decision variables:

The number of the candidate substations is limited, and the substation that has been built won't be removed in the sequent stages, so the substation decision variables actually reduce stage by stage. In order to obtain the substation optimal planning that has known in the target year, we could determine the substation that the load (existing and new) belongs to in each stage with reference to the service range of every substation in the target year. The substation decision variables in each stage just include the substations that the load of this stage belongs to and their adjacent substations.

(2)Capacity decision variables:

The substation capacity type to be chose in each stage is determined by the substation capacities in the target year. In order to achieve the optimal investment of the whole planning period, the load rate limit is relaxed in the previous stages, except for the load rate in the final stage.

When $k<T$, $\sum_{j\in J_i(k)} W_j(k) \le S_i(k)\cos\varphi$

When $k=T$, $\sum_{j\in J_i(k)} W_j(T) \le S_i(T)e(S_i(T))\cos\varphi$ (3)

3.2 The dynamic programming algorithm of the model

The top-bottom algorithm of the dynamic programming is used.

(1)To determine the effective state vertex in Fig.1, we could obtain a valid state set according to the heuristic rules of section 3.1 and number the state vertex stage by stage, e.g. the source code is 0, and the closed point is numbered n-1 (n is the number of all states vertices).

(2)Calculate the weight value of each edge in Fig.1. For the state $S_{k,i}(i=1,2,\cdots,n_k)$, decide if the combination of $S_{k,i}$, and each state in stage k+1 is valid. If invalid, we can set the edge weight to infinite, which indicates the path is not working; if valid, the value of the edge weight is calculated. For example, the weight of the edge between the state vertex S_{11} and S_{22} indicates the difference between the cost objective function of the state S_{11} and S_{22}. $c(S_{k-1,i},S_{k,j})$ （$i=1,2,\cdots,n_{k-1}$） denotes the cost from state i in stage k-1 to state j in stage k, so each edge weight is obtained in Fig.1.

(3) The minimum cost of every state vertex to the source could be determined by using the cost recursive formula stage by stage.

$$\begin{cases} C(S_{k,j},0) = \min\limits_{i=1,2,\cdots,n_{k-1}} \left[C(S_{(k-1),i},0) + c(S_{k-1,i},S_{k,j}) \dfrac{1}{(1+r)^t} \right] \\ C(S_0) = 0 \end{cases} \quad (4)$$

Where, $C(S_{k,j},0)$ is the minimum cost from state j in stage k to the initial phase; $C(S_{(k-1),i},0)$ is the minimum cost from state i in stage k-1 to the initial phase; n_{k-1} is the number of states in stage k-1; t is the discounted number of years in stage k; $C(S_0)$ is the initial costs.

At the same time, the information of the optimal path and costs from each state in each stage to the source is respectively kept in $P(k,j)$ and $C(S_{k,j},0)$, $k=1,2,\cdots,T$; $j=1,2,\ldots,n_k$, n_k is the number of states in stage k.

(4)By using the information that is stored in $P(k,j)$ and $C(S_{k,j},0)$, we can push forward and down back to the source from the closed point in stage T and determine the optimal route in Fig.1, that is the optimal strategy for the dynamic programming problem.

The whole algorithm is mainly composed of three parts. The step (1),(2) above are initialization: $C(S_{k,i},0)$ $k=1,2,\ldots,T$; $j=1,2,\ldots,n_k$ are initialized to the maximum value, $C(S_0)$ is initialized to 0, and $P(k,j)$ is initialized to -1. The step (3) is the local optimization to determine the optimal sub-strategies of each state vertex. The step (5) is the global optimization to determine the global optimal strategy of the whole planning period from closed point to the source.

4. EXAMPLE AND ANALYSIS

Table 1
The total load supplied from the substation in each stage

Substation code	Stage 1/MW	Stage 2/MW	Stage 3/MW
1	15.3	12.53	13.44
2	33.75	67.5	67.5
3	85.05	85.05	127.58
4	21.96	85.05	85.05
5	21.24	25.47	41.06
6	46.21	85.05	105.26
7	0	27.68	40.41
8	0	67.5	67.5

Table 2
The substation capacity in each stage

Substation code	stage1/MW	stage2/MW	stage3/MW
1	10+16	2×31.5	2×31.5
2	1×50	2×50	2×50
3	2×63	2×63	3×63
4	20+12.5	2×63	2×63
5	1×31.5	1×63	2×63
6	2×63	2×63	3×63
7	0	2×50	2×50
8	0	2×50	2×50

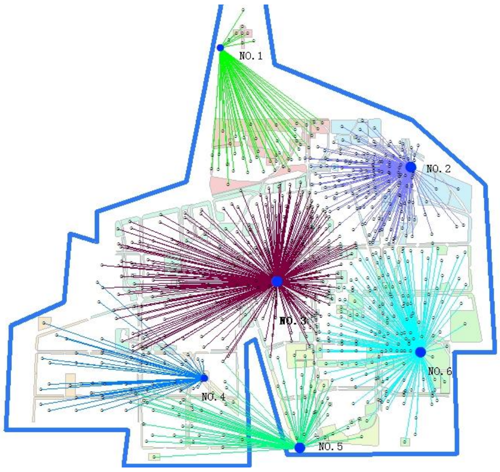
To illustrate the application of the proposed planning model, it was applied to the distribution substation optimization planning of a development zone in a city. The development zone has six original substations, whose position are shown in Fig.2.

The optional capacity set of the new and the existing substations is {1×31.5、2×31.5、1×50、2×50、3×50、1×63、2×63、3×63}. The total load of 2020 forecast is 76.3×10^4 kW. To meet the load requirements, the new substations numbered 7,8 in Fig.2 should be built.

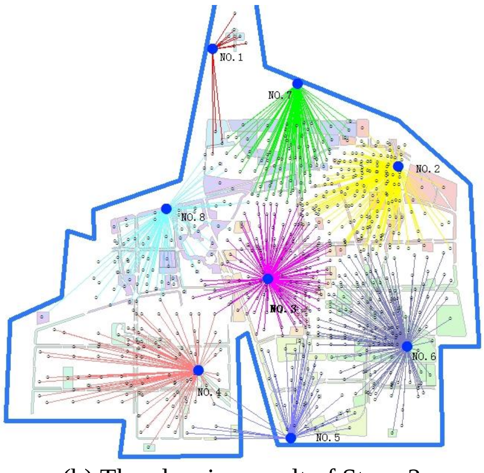
Parameters such as the costs of the substation are in accordance with literature [6]. Economic life is 20 years; the power factor is 0.9; the time-interval of the planning period is 5-year.

The service areas are described in Fig.2; the area of load supplied from the substations in each stage is shown in Table 1; the values of the substation capacity in each stage are described in Table 2.

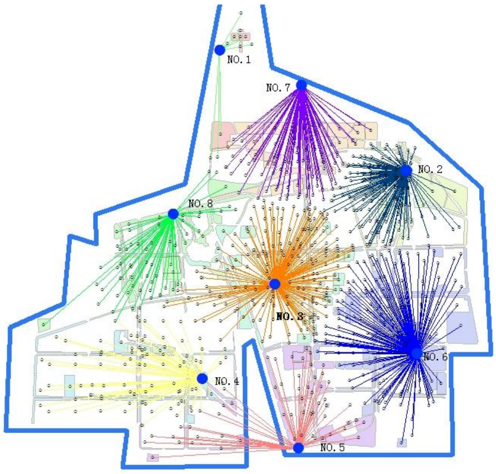
It can be seen from Fig.2 that the new substations 7,8 are put into construction at the second stage, and their capacities can meet the need of the load increment. The service range of every substation at each stage as well as the construction plan of the substations is reasonably practicable.



(a)The planning result of Stage 1



(b) The planning result of Stage 2



(c) The planning result of Stage 3

Fig.2 The service area of the substation in each stage

5. CONCLUSION

This paper proposes a new method about the distribution substation multi-stage planning and implement it by establishing a mathematical model using dynamic programming method. The optimal substation building program of the whole planning period is obtained on the basis of the known condition that the number of the new substations and the capacity of each substation in the target year. The final example shows that the method in this paper has some practical significance.

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