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Optimal planning of high voltage distribution substations

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Abstract Aimed at solving the problem of optimal planning for high voltage distribution substations, an efficient method is put forward. The method divides the problem into two sub-problems: source locating and combinational optimization. The algorithm of allocating and locating alternatively (ALA) is widely used to deal with the source locating problem, but it is dependent on the initial location to a large degree. Thus, some modifications were made to the ALA algorithm, which could greatly improve the quality of solutions. In addition, considering the non-convex and non-concave nature of the sub-problem of combinational optimization, the branch-and-bound technique was adopted to obtain or approximate a global optimal solution. To improve the efficiency of the branch-and-bound technique, some heuristic principles were proposed to cut those branches that may generate a global optimization solution with low probability. Examples show that the proposed algorithm meets the requirement of engineering and it is an effective approach to rapidly solve the problem of optimal planning for high voltage distribution substations.

Keywords high voltage distribution substation, sources locating, ALA algorithm, branch and bound technique, combinational optimization

1 Introduction

The high voltage (HV) distribution substation plays an important role in power systems, which has a great effect on the security and quality of power supply. It is known that to determine the proper locations and sizes of high voltage substations, both the result of spatial load forecast and the structure of the electric power network should be considered.

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Several methods have been proposed in Refs. [1–4] for optimizing the locations and sizes of distribution substations. But they are proposed either on the basis of giving candidate substations' locations in advance or on the assumption that the load density is identical for the whole area. Then, an approach reported in Ref. [5], which divides the whole problem into two sub-problems—substation locating and combination optimization, has been utilized and proved to be practical. It also has the advantage of being able to obtain the optimal size, location and service areas of each of the high voltage (above 35 kV) substations automatically, while having no need of getting the candidate substations' locations in advance [6]. However, the algorithm used in solving the substation locating sub-problem, with the name of substation locating, using the ALA algorithm, is found to be significantly affected by the substation's initial location. The ploughing-around combination algorithm, which is used in solving the sub-problem of combination optimization, always results in a prohibitively long computation time when the scale of the problem is large, while the optimization of the solution may not be sure.

To avoid the problems listed above, some modifications have been made in the ALA algorithm from Ref. [5], and the branch-and-bound technique is adopted to solve the sub-problem of combination optimization, where some heuristic rules are utilized to cut the branches with low probability in generating the global optimal solution. Examples show that the approach proposed in this paper can obtain a better solution than that from Ref. [5]. With the computation significantly reduced, it becomes more practical in searching for an optimal planning solution of high voltage distribution substations.

2 Mathematical models

The optimization problem of the HV distribution substation is to make the decision on the location and size of each substation, which properly supplies the particular region at a given load level with less investment and operational cost.

In this paper, according to the geographic distribution of actual consumers, the service area of the power distribution system is divided into lots of small irregular areas, which are called "sectors". Each has a load point in its center and acts

as the load consumption of customers in it. A substation's service area is defined as the region covered by its feeders. Thus, the general problem of the location and size of the substation is formulated as follows

$$\begin{aligned} \min C &= C_1 + C_2 + C_3 & (1) \\ \text{s.t. } \sum_{j \in J_i} W_j &\leq S_i e(S_i) \cos \varphi \quad i = 1, 2, \dots, N \\ C_1 &= \sum_{i=1}^n \left\{ f_1(S_i) \left[\frac{r_0(1+r_0)^{m_s}}{(1+r_0)^{m_s} - 1} \right] + u(S_i) \right\} \\ C_2 &= \alpha \sum_{i=1}^N \sum_{j \in J_i} W_j^2 \xi d_{ij} \\ C_3 &= \beta \left[\frac{r_0(1+r_0)^{m_1}}{(1+r_0)^{m_1} - 1} \right] \sum_{i=1}^N \sum_{j \in J_i} \xi d_{ij} \\ \alpha &= \frac{\alpha_1 \alpha_2 \alpha_3}{U^2 \cos^2 \varphi} \end{aligned}$$

Here, C_1 —the investment cost and annual operational cost of substations, C_2 —the estimation of the cost of energy losses on the feeders, C_3 —the investment cost of the secondary feeders, N —the total number of substations (and n is the number of the future substations—the substations to be constructed in the future), S_i —the capacity of substation i , $e(S_i)$ —the loading coefficient of transformers in substation i , m_1 —the expected economic life of secondary feeders (years), r_0 —the annual interest rate, m_s —the expected economic life of substations (years), $f_1(S_i)$ —the investment cost of future substation i (and the investment of the existing substation is 0), $u(S_i)$ —the annual operating cost of substation i , W_j —the load magnitude of load point j (real power), J_i —the set of load points to be served by substation i , d_{ij} —the Euclidean distance between substation i and load point j , ξ —the terrain zigzag coefficient, α —the conversion rate of feeder loss, α_1 —the pricing of electricity, α_2 —the resistance on unit length of secondary feeders, α_3 —the annual loss hours, U —the voltage of secondary feeders, $\cos \varphi$ —the power coefficient, β —the investment cost on unit length of secondary feeders.

In order to simplify the problem, the nonlinear cost of the investment and operational losses of the secondary feeders can be assumed linear. Let

$$\bar{W} = \frac{\sum_{j=1}^M W_j}{M} \quad (2)$$

where M is the total number of the load points in the substation's serving area, and \bar{W} is the average of load magnitude in the substation's serving area, then

$$\begin{aligned} C_2 + C_3 &= \alpha \sum_{i=1}^N \sum_{j \in J_i} W_j^2 \xi d_{ij} + \beta \left[\frac{r_0(1+r_0)^{m_1}}{(1+r_0)^{m_1} - 1} \right] \sum_{i=1}^N \sum_{j \in J_i} \xi d_{ij} \\ &\approx \left\{ \alpha \bar{W} + \frac{\beta}{\bar{W}} \left[\frac{r_0(1+r_0)^{m_1}}{(1+r_0)^{m_1} - 1} \right] \right\} \sum_{i=1}^N \sum_{j \in J_i} W_j \xi d_{ij} \end{aligned}$$

Furthermore, let

$$\gamma = \alpha \bar{W} + \frac{\beta}{\bar{W}} \left[\frac{r_0(1+r_0)^{m_1}}{(1+r_0)^{m_1} - 1} \right] \quad (3)$$

$$f_2(S_i) = f_1(S_i) \frac{r_0(1+r_0)^{m_s}}{(1+r_0)^{m_s} - 1} + u(S_i) \quad (4)$$

Then, Eq. (1) can be simplified as follows

$$\begin{aligned} \min C &= \sum_{i=1}^N f_2(S_i) + \gamma \sum_{i=1}^N \sum_{j \in J_i} W_j \xi d_{ij} & (5) \\ \text{s.t. } \sum_{j \in J_i} W_j &\leq S_i e(S_i) \cos \varphi \quad i = 1, 2, \dots, N \end{aligned}$$

Here, γ is the average annual cost on unit length of secondary feeders with unit load flow, including the cost of investment and power losses.

In the above procedure, the error should exist in the linearization of the cost on secondary feeders, and it can be reduced to near zero when the magnitude of each load point is approximately equal, which can be realized by a proper division of the load sectors in a geographic information system.

The first item on the right side of Eq. (5), namely the investment and operational cost of substations, depends only on the combination schemes of substations and has nothing to do with the sites of substations in the formation. It is a problem of combinational optimization. The second item in Eq. (5) is related to the sites of substations, representing a problem of source locating. The whole problem of Eq. (5) is the large-scale optimization, which is composed of two sub-problems, namely the combinational problem and the source locating problem [5].

The problem of Eq. (5) is complicated. In addition, the cost of the investment and power losses of secondary feeders will have an effect on the combination of substations, so it cannot be solved solely by either classical optimization approaches or even modernly used ones such as genetic algorithms (GA) and simulated annealing (SA) algorithms, etc. In this paper, based on the approach proposed in Ref. [5], the problem is dealt with two composed sub-problems as the sub-problems of substation locating and combination optimization. To solve the problem of substation locating, the modified ALA method is adopted. For the other sub-problem, namely the problem of combinational optimization, the branch-and-bound technique is used. In addition, to reduce the computational burden, a heuristic method is suggested, which cuts the branches with low probability in the process of generating the global optimization solution.

3 Algorithm for the problem of source locating

Given the particular combinational scheme (of the number and types of substations) to be constructed, the $\sum_{i=1}^N f_2(S_i)$ and

$S_i e(S_i) \cos \varphi$ in Eq. (5) are determined as constants, which can be regarded as C_1 and $C_2(i)$. Therefore, Eq. (5) becomes the sub-problem of source locating, and can be expressed as

$$\begin{aligned} \min C &= C_1 + \gamma \sum_{i=1}^N \sum_{j \in J_i} W_j \xi d_{ij} \\ \text{s.t. } \sum_{j \in J_i} W_j &\leq C_2(i) \quad i = 1, 2, \dots, N \end{aligned} \quad (6)$$

In the problem of source locating, not only the locations of future substations should be determined, but also the service area of each of the substations should be decided, i.e., allocate each of the load sectors to a proper nearby substation supply. In this paper, the modified ALA algorithm is used to solve the problem.

3.1 Traditional ALA algorithm

The traditional ALA algorithm is widely used in problems of source locating. It has 3 processes as follows.

1) Allocating process

Suppose that the locations of substations $(x_{i,t}, y_{i,t})$, $i = 1, 2, \dots, N$, are already known (the locations of substations are randomly selected at the first, and are iterated for the others), and the remaining task is to determine the load sets J_i , $i = 1, 2, \dots, N$, i.e., to allocate each of the load points to one proper nearby substation while satisfying the substation capacity constraint.

2) Locating process

Determine the location of the central point of each of the load sets J_i , $i = 1, 2, \dots, N$, which will be set as the location of substation i for the next iteration.

3) The above two procedures are iterated until the objective function cannot be significantly improved.

3.2 Modifications to traditional ALA algorithm

In this paper, a weakness is found in the traditional ALA algorithm, and modifications are made.

The weakness in traditional ALA algorithm: the solution is sensitive to the substation's initial location. It shows that different initial sites of the substations' locations always result in different solutions. In practice, the initial sites of substations are always taken from the planner's willingness; they are not so good at all sometimes, which is harmful to get a better solution. Especially in cases when the capacities of the substations are different with each other, their relative positions are always kept unchanged during the iteration, so that the final solution depends on the relative locations of the substations given initially.

In this paper, two modifications have been made.

1) To escape from a local optimal solution, a random perturbation mechanism is introduced. When the ALA converges at a stagnation point, the position of each of the substations is to be moved randomly by a given distance, after which

the iteration goes on. If all the substations still return to the stagnant positions, the stagnation points are considered as the optimal solution in a large scale. Otherwise, the iteration continues.

2) In the case when capacities of the substations are different, a two-step process is undertaken. First, let each of the substations with the biggest capacity permitted in the optimization and carry out the iteration, to calculate the initial locations of the substations for the next step. Then, the substations are set with their actual capacities and their initial locations are positioned at the sites obtained from the first step, with the larger substations locating at the sites with the heavier loads' supply. Then begin another ALA iteration to derive the final solutions.

It has been shown that the ALA algorithm with the modifications given above has better performance.

4 Algorithm for combination optimization

The problem of combination optimization in substation planning is to seek the set $T_m = \{S_1, S_2, \dots, S_n\}$, which gives the minimum object function from the feasible solutions set K , while subjects to the constraints in Eq. (5), formulated as follows

$$f(T_m) = \min_{\forall T_i \in K} f(T_i) \quad (7)$$

In this paper, the object function for combinational optimization is first simulated to show its feature in the spatial case, and then the branch-and-bound algorithm is proposed.

4.1 Simulation of the objective function for combinational optimization

In the case, it is supposed that there are three kinds of substations available in the form of capacities, which can be listed as S_{\max} , S_{mid} and S_{\min} . Consequently, the number of substations required is assumed as n_x , n_d and n_n .

To meet the loads' demand, the following equation should be maintained

$$n_x S_{\max} + n_d S_{\text{mid}} + n_n S_{\min} \approx \frac{\sum W - \sum P}{e \cos \varphi} \quad (8)$$

Here, $\sum W$ is the total amount of loads in the whole planning region, $\sum P$ is the total active power capacity of existing substations, and e is the loading coefficient of transformers in the substation.

From Eq. (8), it can be seen that only 2 variables among n_x , n_d and n_n are independent, that is to say, given each two variables among these three the third can be determined. This character can be used to reduce the dimensionality of the problem and give an outlook on the feature of the object function.

In this paper, it is demonstrated on a practical urban distribution system planning project, where the capacities of the substations available are 2×31.5 , $(31.5 + 20)$ and 2×20 MVA, and the numbers for these substations required are n_x , n_d and n_n . Here, we let the n_x and n_d be independent, and then the appearance of the object function is shown as Fig. 1.

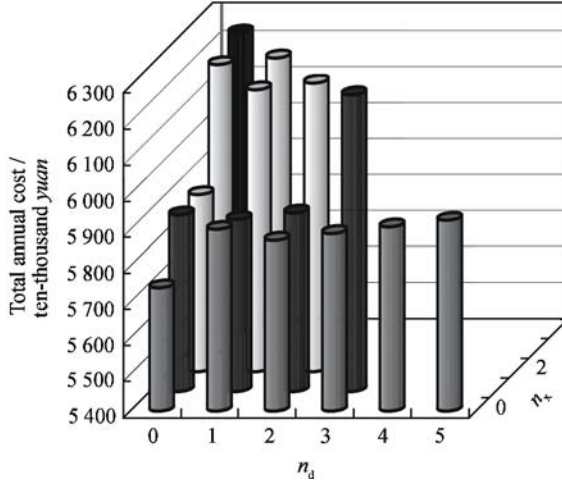


Fig. 1 Configuration of objective function

From Fig. 1, it can be found that the object function for the problem of combinational optimization is neither convex nor concave. Moreover, regarding the complexity in solving the problem of source locating for each case of the combination, it is difficult to be solved by the approaches normally used. However, even the new types of algorithms such as SA and GA are still inefficient. For the sake of both quality and efficiency, the branch-and-bound algorithm is used in this paper. Some heuristic principles are also utilized to reduce the amount of calculations, making the method more practical.

4.2 Solution processes for combination optimization

Let n_1 be the possible maximum number of future substations, and n_2 be the minimum. Thus

$$n_1 = \frac{\sum W - \sum P}{(Se)_{\min} \cos \varphi} + I_T, \quad n_2 = \frac{\sum W - \sum P}{(Se)_{\max} \cos \varphi}$$

where

$$(Se)_{\min} = \min_{S_i \in Q} S_i e(S_i),$$

$$(Se)_{\max} = \max_{S_i \in Q} S_i e(S_i).$$

Q is the set of proposed substation capacities available in the planning period, and I_T is a slack variable as a positive integer that is given in advance.

Then the solution strategy is proposed as follows.

1) Let $n = n_2$, where n is the number of future substations to be constructed in the project.

2) Let the capacities of each of the substations to be constructed in the project be $(Se)_{\max}$, and then the sub-problem of source locating is performed.

3) Calculate the sum of the loads, named as $L_{i,c}$ ($i = 1, 2, \dots, n$), in the service area of each new substation in project. Arrange the new substations in an ascending order by the corresponding value of $L_{i,c}$. Then determine the actual required capacities of each of the new substations, named as $S_{i,c}$ ($S_{i,c} \in Q$) according to the load of $L_{i,c}$. The solution $T_{n,c} = \{S_{1,c}, S_{2,c}, \dots, S_{n,c}\}$ obtained here is to be used as a reference in the branch-and-bound algorithm.

4) Based on $T_{n,c}$, the branch-and-bound algorithm is utilized to obtain an optimal solution T_n , where the number of the new substations to be constructed is set as n . Then the objective function is calculated as f_n , and let f_n be the current optimal solution if $f_n < f_{\min}$, where f_{\min} is the optimal solution found before.

5) Let $n = n + 1$, and if $n \leq n_1$ go to step 2), otherwise end.

4.3 The branch-and-bound algorithm for combination optimization

As it is well known that in solving problems within limited feasible solution space, the branch-and-bound method separates the whole solution space into several smaller subsets (which are called branches) successively. It finds the optimal solution for each of the branches as a tag (namely bound). Then, the branches whose tags are no better than the optimization solution found are not considered (namely branches cut). So the search space for optimization can be much smaller.

4.3.1 Principle for design branches

Assumption With several values of capacities in the given $T_{n,c} = \{S_{1,c}, S_{2,c}, \dots, S_{n,c}\}$ ($n = n_2, n_2 + 1, \dots, n_1$) changed, while the locations of substations in $T_{n,c}$ unchanged, the ALA algorithm is performed, and the new solution $T_n = \{S_1, S_2, \dots, S_n\}$ is obtained. If the locations of substations in the new solution T_n , named as (x_i, y_i) ($i = 1, 2, \dots, n$) do not differ much from those in $T_{n,c}$, known as $(x_{i,c}, y_{i,c})$, then it is claimed that the values of capacities are changed to S_i at the location $(x_{i,c}, y_{i,c})$ ($i = 1, 2, \dots, n$).

From the assumption above, the treelike solution distribution structure can be worked out by changing the capacity of substations at locations $(x_{i,c}, y_{i,c})$ ($i = 1, 2, \dots, n$) to any value available. When $n = 3$, and the capacities available are S_{\max} , S_{mid} and S_{\min} , the treelike structure of part of the solution space can be shown in Fig. 2.

By selecting values of capacity available at the substation locations $(x_{i,c}, y_{i,c})$ ($i = 1, 2, \dots, n$), the feasible solution $T_n = \{S_1, S_2, \dots, S_n\}$ can be obtained. Let $(x_{i,c}, y_{i,c})$ be the initial location of the i th substation in T_n , after several ALA iterations, the objective function of the substation

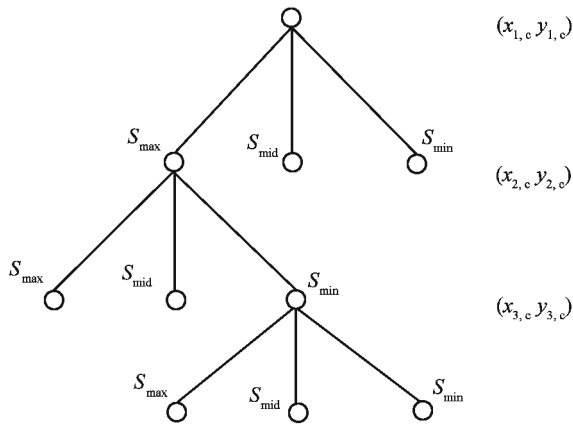


Fig. 2 Structure of solution tree

combination optimization and the location of each of the substations can be found out.

4.3.2 Heuristic principles for branch cut

For the sake of efficiency, the following three heuristic rules are proposed in this paper to cut the branches with low possibility of being the optimal solution.

Principle 1 For the reference solution $T_{n,c}$ ($n = n_2, n_2 + 1, \dots, n_1$) is obtained under the condition that the number of new substations to be constructed be as n , and the capacity of the substation set to its top limits, then the $C_2(i)$ ($i = 1, 2, \dots, N$) in Eq. (6) should be the possible maximum value. Thus, the cost of investment and power losses on the feeders (the item of $\gamma \sum_{i=1}^N \sum_{j \in J_i} W_j \xi d_{ij}$ in Eq. (6)), should be the least among all the cases where the number of new substations to be constructed is set as n . Therefore, some capacities of the substations in $T_{n,c}$ should be reduced, which could cut the investment of substations down to get the better solution.

Principle 2 For the same reason in Principle 1, the capacities larger than $S_{i,c}$ at location $(x_{i,c}, y_{i,c})$, ($i = 1, 2, \dots, n$), are not considered in the latter search space.

Principle 3 If the total load in the service area of substation i is larger than that of substation j ($i, j = 1, 2, \dots, n$, and $i \neq j$), in the reference solution of $T_{n,c}$ ($n = n_2, n_2 + 1, \dots, n_1$), then such searching cases as making the capacity of the substation at $(x_{i,c}, y_{i,c})$ less than that of the substation at $(x_{j,c}, y_{j,c})$ are eliminated from consideration.

Using the above three heuristic principles with the constraint that load demands should be met by substations in

the whole region, lots of unsuitable branches can be deleted, and the approach performs more efficiently. Practically, the possibility of the optimization solution being among the deleted branches is very low.

Based on the reference solution of $T_{n,c}$ ($n = n_2, n_2 + 1, \dots, n_1$), the branch-and-bound algorithm can be used to find the local optimal solution in the case that the number of new substations to be constructed is known as n , and then the global optimization is determined by selecting the one with the lowest objective function among these local solutions.

5 Test results

In this paper, an example of the actual urban distribution power system planning project is proposed. There are 4 voltage levels involved, which are 220 kV, 66 kV, 10 kV and 380 V (220 V). The planning period is from the year 1995 to 2010. In the procedure of load distribution forecast, the spatial load-sector method is used. The capacities available for substations to be constructed in the project are 2×31.5 , $(31.5 + 20)$ and 2×20 MVA. Comparison is made between the algorithm in this paper and that from Ref. [5] on the result of the planning of 66/10 kV substations as listed in Table 1.

From Table 1, it can be found that the combination schemes of substations' capacities from these two algorithms are the same, but the result of substations' locations obtained from the algorithm in this paper is better than those from Ref. [5]. This is due to the improvement made in the ALA algorithm in the sources locating procedure. Therefore, it can be concluded that the modifications made in this paper are useful, and the algorithm in this paper converges more quickly.

For further comparison, 10 groups of load distribution cases are produced at random, while the sites of the loads remain the same as those from the example above. A comparison is made on these 10 groups of load cases using the algorithm in this paper with that from Ref. [5], the results are shown in Table 2.

From Table 2, it can be found that in 6 cases the substation combination solutions obtained by the algorithm proposed in this paper are much better than those from Ref. [5], while in the other 4 cases, the solutions are the same. Due to the improvement in the ALA algorithm, the solutions of substation locations in this paper are better than those from Ref. [5] for all cases. Summarily, for all the cases, the algorithm proposed in this paper performs better than that from Ref. [5], while the time consumption is about 2/5 of that from Ref. [5].

Table 1 Comparison of optimal planning result for high voltage distribution substations of a city

Algorithm	Substations to be constructed			Annual value of investment and operational cost of substations/ ten-thousand yuan	Annual value of investment and loss cost of secondary feeders/ ten-thousand yuan	Total annual cost/ ten-thousand yuan	Time consumed/ s
	2×31.5 / MVA	$31.5 + 20$ / MVA	2×20 / MVA				
This paper	0	0	7	1 899.99	3 706.92	5 606.92	27.218
In Ref.[5]	0	0	7	1 899.99	3 709.18	5 609.17	68.25

Table 2 Comparison of optimal planning result for high voltage distribution substations with 10 groups of random load data

Index of load data	Algorithm	Substations to be constructed			Annual value of investment and operational cost of substations/ ten-thousand yuan	Annual value of investment and loss cost of secondary feeders/ ten-thousand yuan	Total annual cost/ ten-thousand yuan	Time consumed/ s
		$2 \times 31.5/$ MVA	$31.5 + 20/$ MVA	$2 \times 20/$ MVA				
1	This paper	0	1	7	2 188.16	2 704.89	4 893.05	36.734
	Ref. [5]	1	0	7	2 204.91	2 711.69	4 916.60	79.078
2	This paper	0	1	5	1 645.31	3 710.97	5 356.28	24.048
	Ref. [5]	0	1	5	1 645.31	3 713.62	5 358.93	47.406
3	This paper	1	2	4	1 978.72	3 099.31	5 078.03	39.015
	Ref. [5]	0	3	4	1 950.23	3 794.85	5 745.08	86.156
4	This paper	0	1	6	1 916.74	3 281.10	5 197.84	26.078
	Ref. [5]	0	1	6	1 916.74	3 303.02	5 219.75	86.483
5	This paper	0	1	7	2 188.16	2 877.06	5 065.23	27.891
	Ref. [5]	0	1	7	2 188.16	3 281.24	5 469.41	87.058
6	This paper	0	1	6	1 916.74	3 266.14	5 182.88	23.734
	Ref. [5]	0	0	8	2 171.42	3 023.38	5 194.80	89.493
7	This paper	0	1	7	2 188.16	2 789.76	4 977.93	19.687
	Ref. [5]	0	2	5	1 933.48	3 053.54	4 987.02	66.812
8	This paper	0	1	6	1 916.74	2 794.93	4 711.67	27.500
	Ref. [5]	0	0	6	1 628.56	3 088.39	4 716.96	46.094
9	This paper	0	0	6	1 628.56	3 149.03	4 777.59	15.875
	Ref. [5]	0	0	6	1 628.56	3 151.04	4 779.60	40.469
10	This paper	0	0	7	1 899.99	3 183.41	5 083.40	25.984
	Ref. [5]	0	0	7	1 899.99	3 183.50	5 083.58	57.359

Thus, it can be concluded that the algorithm proposed in this paper is more effective.

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6 Conclusions

Based on the approach presented in Ref. [5] of dividing the HV distribution substation optimization problem into two sub-problems, the sub-problems of substation locating and combination optimization, some further work is carried out in this paper.

1) Modifications are made in the widely-used ALA algorithm for the problem of source locating, which can make up for the weakness of a traditional ALA algorithm that the solution is much sensitive to the locations given initially.

2) Display that the sub-problem of substation combination is non-convex and non-concave by simulation, and the branch-and-bound technique is suggested to solve the problem, with some principles proposed to cut the branches with little probability of being the optimal solution.

Examples show that the modified approaches suggested in this paper are more effective and more practical.

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