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Optimal Placement of Multiple Feeder Terminal Units Using Intelligent Algorithms

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Abstract: In order to solve the placement problem of three kinds of feeder terminal units (FTU) in the distribution network, this paper proposes a novel mathematical model. The model considers economic cost and electricity supply reliability from the perspective of life cycle cost. The reliability algorithm in this model is established for the distribution network configured with centralized feeder automation. Different evaluation indices of reliability and the importance of several kinds of customers are also considered in this model. Aiming at the reliability evaluation in this model, this paper puts forward the reliability analysis method for the distribution network with three kinds of FTUs. In view of the difficulty to express the reliability of distribution network in a formula with decision variables, and the non-deterministic polynomial hard (NP-hard) nature of this model, a variety of intelligent algorithms are applied to solve the model. The feasibility and effectiveness of the model and methods for FTUs placement optimization problem are verified by a case study of the Roy Billinton test system (RBTS) Bus 5 system.

Keywords: distribution automation; feeder automation; feeder terminal unit; reliability; placement optimization problem; intelligent algorithms

1. Introduction

With the development of social economy, customers are increasingly demanding the reliability of distribution networks, and the impact of electricity outages is becoming more and more obvious. Distribution automation (DA) is an effective means to improve the reliability of electricity supply and achieve monitoring and control of the distribution network under intact or fault conditions. The distribution automation system (DAS) consists of the distribution master station, the distribution slave stations, and the distribution terminal units (DTU), and adopts a hierarchical structure design. The DTU is a device installed on a pole-mounted switch, a switching station, or a ring main unit (RMU). It has the functions such as monitoring the state of the primary equipment in distribution network, communicating with the master station or slave stations, and controlling the operation of the primary equipment. Feeder automation (FA) is one of the core components of DA. When a fault occurs in the feeder, FA can help to locate and isolate the fault and restore electricity, thus shortening the outage time of some customers and improving the reliability of distribution network.

The realization of FA depends on the FTUs, which is a kind of DTU. When the distribution network adopts the centralized feeder automation mode, FTUs play a very important role in dealing with feeder faults, directly affecting the time it takes to locate and isolate faults. In China, FTUs generally fall into three categories: the "one remote" terminal unit, the "two remote" terminal unit and the "three remote" terminal unit, which are named according to their functions. As long as the terminal unit makes the staff know whether fault current flows somewhere in the feeder without measuring the feeder manually, it is considered that this terminal unit meets the meaning of “remote” in Chinese. The numbers “one”, “two”, and “three” can be understood as describing the level of automation this terminal unit brings to the distribution network, which can be sensed through the roles of the three types of FTUs in the fault management. The “One remote” terminal unit can indicate at the feeder site whether the fault current flows through the corresponding switch, and can help maintenance operators find the fault quickly when they are patrolling the feeder. The “Two remote” terminal unit can measure the current and voltage of the corresponding switch. Therefore, it can identify whether the fault current has flowed through the switch. If it is, it will communicate this information to the master station, which can help the operators in the master station to determine the feeder segment where the fault may exist remotely. On the basis of the “two remote” terminal unit, the “three remote” terminal unit has an additional function: the operators in the master station are able to remotely control the corresponding switch, reducing the time to isolate the fault. To be more concise, we call the sectionalizing switch (SS) with a “one remote”/“two remote”/“three remote” terminal unit as a type A/B/C switch, and call the SS without any FTU as a type D switch.

The number and location of FTUs directly affect the reliability, investment, and operation and maintenance costs of the distribution network. In the China Southern Power Grid Company Limited (CSG, one of the two major power grid companies in China), the planning technical guidelines lack targeted guidance for the placement problem of FTUs, in which it is advised to divide the electricity supply areas according to the load density and equip them with the same type of FTUs for the SSes. However, in order to meet the reliability requirements, guidelines often suggest excessive placement of the “three remote” terminal units, resulting in extremely high investment cost. In this context, significant and urgent investigation is needed to obtain a better trade-off between reliability and economical placement of FTU.

Various papers have been published about optimal placement of SS or remote control switch (RCS). Related models and algorithms have been extensively studied, with SS and RCS formulated in nearly a same way (described as type C switch in this paper). Galias presented a tree-structure based algorithm to compute performance indexes when the positions of SSes are given, and applied it to the radial distribution networks [1]. Bezerra et al. studied the same problem from the perspective of multi-objective optimization [2]. When Izadi et al. study the RCS deployment problem, they focus on financial risk constraints [3]. Izadi et al. added the possible locations on the laterals to the solution of RCS placement problem [4], while Farajollahi et al. took the possible failure rate of the SS into consideration [5]. Safdarian et al. emphasized the influence of RCS on the reliability of distribution network [6]. Moreover, scholars have continued relevant study in the presence of distributed generators recently [7,8].

However, research on placement optimization of FTUs or DTUs is relatively rare. Shammah et al. presented a model of optimal location of remote terminal units (RTUs), which aims to minimize the total cost including the capital costs and the running cost. The node-voltage level is also added in the objective function [9]. Wang et al. also studied this problem, but in the case of integrated cyber-physical distribution systems [10]. The switch with RTU installed in the above two articles is the type C switch in this article. Besides, the fault indicator (FI) placement has drawn attention, including new perspectives (such as multi-objective FI deployment optimization problem [11]), new scenarios (such as in cyber-enabled distribution network [12]) and new methods (such as a mixed integer programming (MIP) based approach [13]).

However, there is a drawback which cannot be neglected with respect to practical distribution networks application. The existence of the type A, B, and C switches are not considered simultaneously in the above obtained solutions. Even though a distribution network installed with three types of FTUs is more likely to obtain a better compromise between reliability and economy. Moreover, traditional reliability algorithms are generally based on the assumption that all SSs are RCSs, so that there also exists a research gap in a tailored method for calculating the reliability of distribution network installed with three types of FTUs, to provide a more accurate evaluation for actual distribution network.

Appropriate intelligent algorithms are also needed to be studied since the reliability of the distribution network is difficult to be formulated explicitly due to topology searching. Furthermore, optimal placement is normally a nonlinear non-convex NP-hard combinatorial optimization problem.

Therefore, this paper proposes a novel mathematical model considering economic cost and electricity supply reliability from the perspective of life cycle cost (LCC). The novelty can be summarized as follows:

- A reliability algorithm for the distribution network with three kinds of FTUs is proposed, by which the roles of three types of FTUs in the process of locating faults, isolating faults, and resuming power supply are clarified. To the best knowledge of the authors, this is also the first attempt to carry out a placement of the three FTUs simultaneously.
- From the perspective of power supply service received by users, various evaluation indexes of reliability are considered. This ensures the high reliability after the model is applied to the distribution network.
- In order to measure the loss of various customers caused by outage more accurately, the importance difference of several kinds of customers is considered in the calculation of outage losses.
- A variety of intelligent algorithms are used and compared to get a satisfactory solution for the proposed model.

This paper is structured as follows. By analyzing three kinds of FTUs' functions in the process of fault management, Section 2 proposes a reliability algorithm for the distribution network with three kinds of FTUs, which is the core content of the outage loss in the objective function. Section 3 provides a practical mathematical model for the FTUs configuration problem, in which both reliability and economy are considered. Subsequently, Section 4 explains the reason of choosing intelligent algorithms and describes how to use ant colony optimization (ACO), discrete particle swarm optimization (DPSO), and genetic algorithm (GA) to solve the model. Section 5 applies the model and algorithms to a test system and discusses the simulation results to obtain several conclusions. Finally, Section 6 summarizes the paper.

2. The Reliability Algorithm

There are several reliability indices which are widely used by utilities, such as system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), average service unavailability index (ASAI), expected unsupplied energy (EENS), and so on. These indices assess the impact of outages on the system or customers from different perspectives, such as frequency and duration.

To calculate these indices as the evaluation of the solution, the reliability of each load point is needed to be calculated first. In order to establish the mathematical model of reliability calculation, it is necessary to clarify the relationship between the fault management procedure and the FTUs.

There are several details about the reliability algorithm which need to be shown. In this paper, it is considered that seven kinds of elements of distribution network are likely to fail, which are lines, transformers, fuses, SSs, tie switches, and loads. For each element, only permanent faults (which lead to sustained interruptions) are considered, while instantaneous faults are not considered. For the reasons of user outages, this paper only considers the element failures of the distribution network, and does not consider the scheduled outages. Besides, the "three remote" terminal units are assumed to be installed on the circuit breaker (CB) at the head of the feeder and the tie switch at the end of the feeder because these positions are very important for reliability.

The Steps will be performed after the fault as follows.

- The normally closed CB which is an adjacent upstream will operates because of the relay protection, and then all of the downstream load points will be de-energized. This process takes a very short time which can be ignored.

- The area where exits any type C switching will be isolated preliminarily, and the power supply for some customers here can be resumed immediately instead of waiting until the fault being located accurately. Preliminary fault location can be done based on the information sent from the FTUs installed on the type B and type C switches, and then the adjacent upstream and downstream type C switches can be opened. This process takes a few minutes.
- Maintenance operators will be arranged to patrol the feeder, check the display of the FTUs installed on the type A switches, and find out which feeder segment the fault exists in. The time spent on this process needs further calculation.
- Maintenance operators will disconnect the adjacent upstream and downstream SSes and tie switches so that all load points outside the faulty feeder segment can be recovered.
- The maintenance operators repair the faulty feeder segment, and then restore the load points connected to the faulty feeder segment after the repair. Normally, this step takes the longest time in the process of fault management.

The procedure of the reliability algorithm for the distribution network with three kinds of FTUs is similar to the procedure of the traditional reliability algorithm, as shown in Figure 1. This procedure is based on failure mode and effect analysis (FMEA). However, the reliability algorithm considering three kinds of FTUs is fundamentally different from FMEA in the analysis and calculation of Steps 3 and 4.

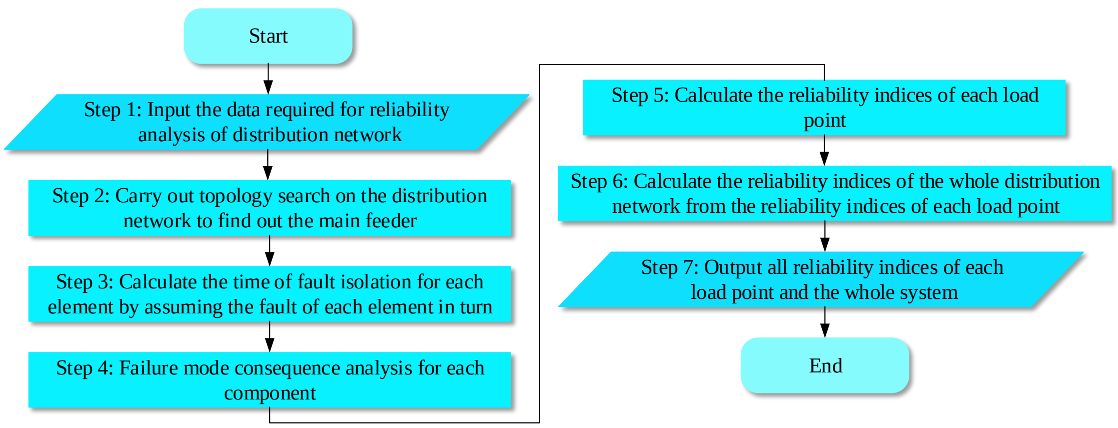

Figure 1. The procedure of the reliability algorithm for the distribution network with three kinds of feeder terminal units (FTUs).

It should be noted that the reliability algorithm of this paper belongs to the analytic method. The characteristic of the analytic method is to traverse every possible fault element in the distribution network and assume that it has a fault (Steps 3 and 4). After the Step 3 and 4 of reliability algorithm are completed, the outage time and outage times of each load point caused by this fault are multiplied by the probability of this fault, which is the first sub step of Step 5. Therefore, it can be considered that the number of faults for each network element is the failure rate of this element.

In this Section, a new reliability algorithm is proposed, with a main contribution lying in the fault isolation time analysis and the failure mode and effect analysis. A simple radial feeder is taken as an example to illustrate the specific implementation of Steps 3 and 4 in the proposed algorithm, as shown in Figure 2. The remaining Steps can be referred to the literature [14].

Let t_1, t_2, and t_3 denote the time for remotely switching in the master station, the time for fault isolation and the time for fault repair, respectively. t_2 consists of the travel time to the faulty feeder (defined as t_{21}), the time for locating the fault (defined as t_{22}), and the time for operating the switches manually to isolate the fault to the shortest feeder segment (defined as t_{23}). The calculation of t_2 can be expressed as:

$$t_2 = t_{21} + t_{22} + t_{23} \tag{1}$$

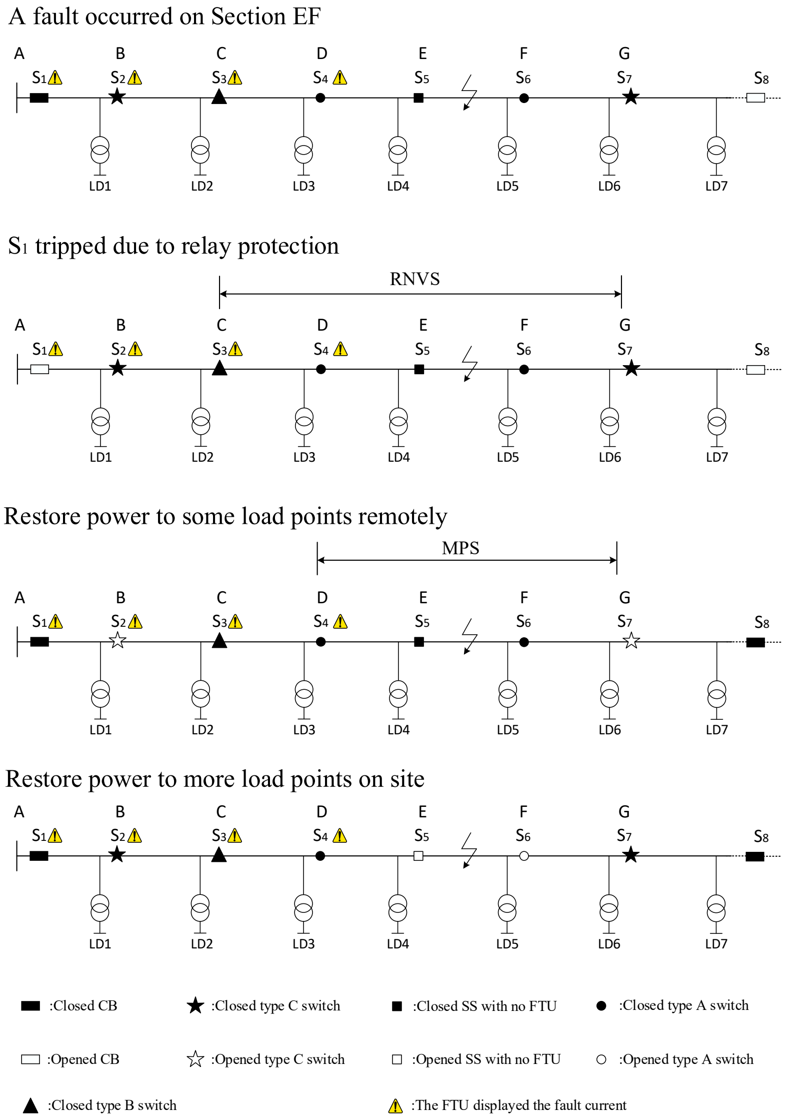

Figure 2. A simple feeder with a fault on Section EF and the process of fault management.

2.1. Fault Isolation Time Analysis

If a fault occurs in segment EF, the CB S1 operates and de-energizes all downstream load points (LD1~LD7). The FTUs on the type B and type C switches upstream to the fault (S1~S3) send the data of fault current to the master station, and the FTUs on the type B and type C switches downstream to the fault (S7) do not send any data about fault current. The minimum range where the fault occurred can be identified as segment CG by the operators in the master station according to the remote data provided by the FTUs of the switches S1, S2, S3, and S7. In this paper, the segment CG is regarded as the remotely non-visual segment (RNVS) which may require further manual inspection. That is to say, RNVS is defined as the feeder segment between the upstream type B switch/type C switch/CB closest to the fault and the downstream type B switch/type C switch/tie switch closest to the fault.

Maintenance operators are dispatched to the RNVS (segment CG) to check all the FTUs installed on the type A switches in the RNVS (S4 and S6). Similar to the switches S1~S3, the switch S4's FTU indicates the fault current by turning on the indicator light, while the switch S6's FTU does not. Then the minimum range where the fault occurred can be reduced to segment DF. In this paper, the segment DF is regarded as the minimum patrol segment (MPS) which may require manual patrol to find out the exact fault location. More precisely, MPS is defined as the feeder segment between the upstream switch or CB with any type of FTU closest to the fault and the downstream switch or CB with any type of FTU closest to the fault.

With the inspection for the MPS (segment DF), the minimum fault segment (MFS) can be found out, which is segment EF in this case. It is easy to understand that the MFS is between the upstream and downstream switches or CBs adjacent to the fault.

The time for locating the fault t_{22} consists of the time for checking the display of the FTUs installed on the type A switches (defined as t_{221}) and the time for patrolling the feeder (defined as t_{222}), which can be calculated as:

$$t_{22} = t_{221} + t_{222} \tag{2}$$

$$t_{221} = n_{A-RNVS} t_A \tag{3}$$

$$t_{222} = l_{MPS} t_p \tag{4}$$

where $n_{A\text{-}RNVS}$ is the number of type A switches in the RNVS, t_A is the time for check one FTU of a type A switches, l_{MPS} is the length of MPS, t_p is the patrol time for per unit length of feeder.

After the fault location is completed, if the first and last switching elements of the MFS cannot be remotely controlled, they need to be operated on the spot manually to isolate the fault. The formula for calculating this time t_{23} is calculated as follows:

$$t_{23} = n_{m-MFS} t_m \tag{5}$$

where $n_{m\text{-}MFS}$ is the number of switching elements without remote control conditions in the MFS, t_m is the time for manual operation of a single switch on site.

2.2. Failure Mode and Effect Analysis

In this Section, the main difference between the proposed reliability algorithm and the traditional reliability algorithm is the criterion of outage time at each load point. For description convenience, the main feeder point (MFP) of an element j is defined as: the intersection point of the main feeder and branch feeder on the minimum path between element j and power point. If element j is a component of the main feeder, then the MFP of element j is the first node of element j. The MFP definition of a load point i is similar to that of element j. Then the associated path (AP) between element j and load point i is defined as: the feeder segment between the MFP of element j and the MFP of load point i.

The outage time T_{ij} of a load point i caused by the failure of an element j is related to the type of the FTUs installed on the switching elements in the AP between faulty element j and load point i. In the following, the outage time T_{ij} of a load point i will be discussed by classification.

Figure 3 is a classification diagram for the outage time T_{ij} analysis.

Circumstance A: Faulty element j is on the branch line, and fuse or CB is installed at the outlet of the branch line.

A1. Element j and load point i are on the same branch line. Load point i cannot be isolated from element j and be restored, so the outage time of load point i is $T_{ij} = t_1 + t_2 + t_3$.

A2. Element j and load point i are not on the same branch line. Element j's failure can be quickly isolated by the fuse or the CB and will not result in outage at load point i, so $T_{ij} = 0$.

Circumstance B: Faulty element j is on the main feeder, or on the branch line without fuse or CB at the outlet of the branch line.

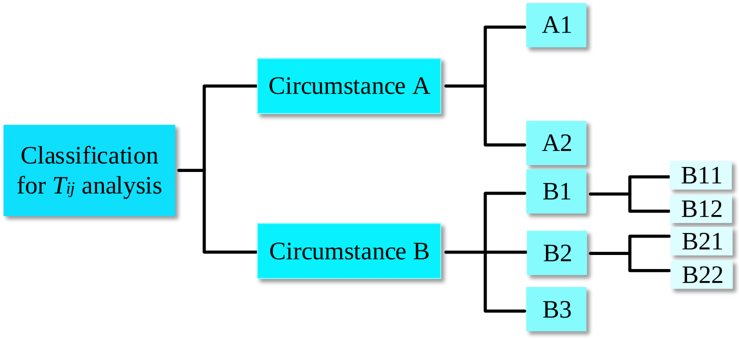

Figure 3. Classification for T_{ij} analysis.

In this circumstance, the fault impact of element j depends on the switch types on the AP between element j and load point i.

B1. There is one or more type C switch on the AP.

B11. The MFP of load point i is upstream to that of element j, or there is a tie switch at the end of the feeder which enables the load points to be transferred to another feeder. Then T_{ij}=t_1 because load point i can be restored by controlling the adjacent upstream and downstream type C switches and the tie switch remotely. As the example shows in Figure 3, switches S2, S7, and S8 are operated remotely when a fault occurs in segment EF, and the outage time of load points LD1 and LD7 is t_1.

B12. The MFP of load point i is downstream to that of element j, and there is not any tie switch at the end of the feeder. The load point i cannot be remotely isolated from the fault or be restored before the fault repair, $T_{ij} = t_1 + t_2 + t_3$.

B2. There is no type C switch on the AP, but there are type A or type B or type D switches.

B21. The MFP of load point i is upstream to that of element j, or there is a tie switch at the end of the feeder. $T_{i\,j}$= $t_1 + t_2$ because load point i can be restored after manual fault location and isolation. In Figure 3, after isolating LD1 and LD7 from the fault remotely, fault location for segment CG is carried out, and finally switches S5 and S6 are operated. Then, load points LD2~LD4 and LD6 regains electricity services. Therefore, their outage time is t_1 + t_2.

B22. The MFP of load point i is downstream to that of element j without any tie switch at the end of the feeder, $T_{i\,j} = t_1 + t_2 + t_3$.

B3. There is no switch on the AP. It means that element j and load point i both belong to the MFS, and element j cannot be restored until element j is repaired, $T_{i\,j}$= $t_1 + t_2 + t_3$. LD5 in the case of Figure 3 is an example of such sub scenario.

3. Mathematical Model

3.1. Decision Variables

To configure FTUs for the switching elements of a given primary distribution network, the decision variable x is the FTU types of the switching elements which are possible and suitable to install FTUs. In order to ensure a certain reliability in the distribution network, the feeder outlet CB and the tie switch between two feeders are supposed to be equipped with "three remote" terminal units. It means that the FTU types of these switching elements do not belong to the decision variables of this optimization model. The value of decision variable x may be 0, 1, 2, or 3, corresponding to the installation of no FTUs, "one remote" terminal unit, "two remote" terminal unit and "three remote" terminal unit respectively.

Each component of decision vector X is the decision variable x for each switch to be considered:

$$X = [x_1, x_2, \ldots, x_m] \tag{6}$$

where m is the number of switches to be considered for configuring FTU.

3.2. Objective Function

This model aims to minimize the LCC of FTU configuration scheme in distribution network. In order to take the impact of FTU configuration scheme on reliability of distribution network into account, the outage loss is incorporated. The objective can be calculated as:

$$\min LCC = C_{inv} + \sum_{t=0}^{n} \frac{1}{(1+r)^t} (C_{mt} + C_{eens}) \tag{7}$$

where C_{inv} is initial total investment cost; C_{mt} is annual cost for FTU maintenance; C_{eens} is annual outage loss of distribution network. Because of the long planning period, the C_{mt} and C_{eens} need to be converted into present value. $\frac{1}{(1+r)^t}$ is the discount coefficient. r is the discount rate, and n is the years of planning period.

3.2.1. Initial Total Investment Cost

The C_{inv} of the distribution FTU configuration scheme is the sum of the purchase and installation costs of the FTU types determined by decision variables as follows:

$$C_{inv} = n_1(pc_1 + ic_1) + n_2(pc_2 + ic_2) + n_3(pc_3 + ic_3) \tag{8}$$

where n_1, n_2 and n_3 are the configuration number of "one remote" terminal units, "two remote" terminal units and "three remote" terminal units, respectively. pc and ic are the purchase and installation costs of FTU respectively. Their subscripts correspond to the type of FTU as the same as the variable n mentioned above.

3.2.2. Maintenance Cost

The C_{mt} of distribution FTU configuration scheme refers to the cost of FTUs failure maintenance and regular maintenance, which is a continuous cost in the life cycle of terminal unit equipment. The current method of cost management for maintenance and overhaul of distribution network equipment adopted by most utilities is a percentage of the initial total investment cost, which can be calculated by:

$$C_{mt} = \eta C_{inv} \tag{9}$$

where η is the proportion of maintenance cost compared to the initial total investment cost.

3.2.3. Outage Loss

The reliability of distribution network with FTUs is the key consideration of this optimization model. In distribution network planning, there is usually a contradiction between the economic objective and the reliability objective. The reliability objective is transformed into a part of the economic objective, to formulate the original multi-objective problem into a single-objective one, and the EENS is used as the reliability evaluation index reflecting the system or load points outage.

Considering that the importance of load points varies in the distribution network due to users' preferences, which leads to different outage losses caused by unit power shortage at different load points. Therefore, a weight coefficient [15] is introduced to measure the differences among load points, as follows:

$$SEENS = \sum_{i \in D} (k\alpha_i + \beta_i + \gamma_i)ens_i \quad (10)$$

where $SEENS$ is the EENS of the system, D is the set of all load points, ens_i is the EENS of the load point i, and $(k\alpha_i + \beta_i + \gamma_i)$ is the weight coefficient.

The parameters α, β, and γ, are used to express the differences of loads in three aspects respectively, namely: life safety, economy, and particularity. α and β belong to {1, 2, 3, 4, 5}. The larger the value is, the greater the impact of losing the load on life safety or economy is. For example, hospital load has a great impact on life safety, so the parameter α of hospital load is at the highest level of 5. Parameter γ indicates the particularity of load. For example, military load or government department load has little impact on life safety and economy, but this kind of load is also important. Their parameter γ can be set as the highest level 5, which makes up the defect that parameter α and β cannot fully reflect the importance of load. Because the loss of life safety is the most serious compared to other losses, the parameter α needs to be multiplied by the factor k to increase the proportion of life safety in these three aspects.

The calculation formula for ens_i is as follows:

$$ens_i = P_i U_i \quad (11)$$

where P_i is the average load of the load point i, U_i is the annual average outage time of the load point i, which can be calculated by the reliability algorithm proposed in the Section 2 of this paper.

In this optimization model, the outage loss of distribution network can be obtained by (12), which refers to the economic loss of the grid and users caused by the outage of distribution network:

$$C_{ens} = SEENS \times \sigma \quad (12)$$

where σ is the outage loss in per unit of power shortage. In order to ensure a high reliability of the distribution network with FTUs configuration, the outage loss of this model includes not only the direct loss caused by the outage, such as income loss of the utilities, production loss of the power consumption enterprises, but also the indirect loss caused by the outage on affecting the enterprise image of utilities and power consumption enterprises, that is, σ is the sum of direct loss and indirect loss of the whole society in unit power shortage.

3.3. Constraint Condition

Different reliability indices quantify the outage of distribution network from different perspectives. If we only consider the EENS which reflects the quantity of unsupplied energy merely, the impact of outage on users cannot be fully described. For example, when the annual EENS of a load point is certain, if the average time of each fault outage is shorter, the annual fault rate will rise, and the load point's user experience on electricity service will get worse. Jonnavithula et al. fitted the outage loss curve by the outage duration and outage loss data of industrial users [16]. It can be seen that the loss caused by multiple short-term outages is greater than that caused by one long-term outage under the condition of unchanged average annual power shortage caused by the grid outage. In order to fully consider the influence of distribution network reliability on load, SAIDI and SAIFI are taken as constraints in this optimization model:

$$SAIDI \leq SAIDI_{\max} \quad (13)$$

$$SAIFI \leq SAIFI_{\max} \quad (14)$$

where $SAIDI_{\max}$ and $SAIFI_{\max}$ are the maximum acceptable values of the corresponding reliability indices. The reliability algorithm proposed in Section 2 is used to calculate the reliability index of each load point firstly, and then the *SAIDI* and *SAIFI* can be calculated according to the formula defined in [17].

4. Model Solution

As mentioned before, a single-objective problem is formulated, which is an NP hard nonlinear combinatorial optimization. Two problems will be faced when the traditional mathematical method is adopted. Firstly, the calculation amount increases exponentially with the scale of distribution network increasing. Additionally, there is likely to be a combinatorial explosion problem [18], which is difficult to be solved by the computer. Secondly, the normal reliability analysis of distribution network depends on the search process of topology structure (such as the process described in Sections 2.1 and 2.2). It makes difficulties to express the reliability of system or load point as an explicit function of decision variables, which limits the application of mathematical optimization algorithm to solving the optimization model in this paper. A large error would be resulted in if the normal reliability algorithm is replaced by the reliability estimation algorithm, making the estimation algorithm incapable of being used to calculate the reliability of the high reliability distribution network with the average outage time of customers in minute level.

Therefore, intelligent algorithms which have fewer restrictions on the optimization model are used to solve the satisfactory solution. By imitating the physical phenomena or group biological behaviors in nature, the intelligent algorithm provides a set of optimization mechanism, which can obtain the satisfactory solution of the optimization problem in acceptable computing time and space. The model-free nature of intelligent algorithms makes it hard to figure out which one has the best performance for a certain optimization problem. Therefore, this paper adopts GA [19], ACO [20] and DPSO [21] to solve the FTU configuration model, and the algorithm with the best performance for the proposed model is found through comparisons from different perspectives. The combination of the three algorithms and the optimization model is elaborated in Appendix A.

5. Case Study and Discussion

The RBTS is adopted with the studied distribution network connecting to Bus 5, to evaluate the feasibility and effectiveness of the proposed model. A single line diagram of this test system is depicted in Figure 4. This example only considers the fault outage, without considering the planned outage. The reliability constraints of the system are SAIDI within 0.55 hr/yr.cust, and SAIFI with 0.8 times/yr.cust. These constraints are based on the research results of the service quality of utilities in urban power grid in China.

5.1. Test System Structure and Parameters

There are 26 load points in the system. The number of users in each load point is set as 50, and the coefficient of life safety parameter is set as 3. The type and average load of each load point are shown in Table 1. The values of parameters α, β, and γ of various load points are listed in Table 2. The failure rate and average repair time of each element are provided in Table 3, and the unit of failure rate for the line is times/yr.km. The length of each branch can refer to [22]. According to the comprehensive cost table of distribution network engineering of Guangdong Power Grid provided by Guangdong Power Grid Planning and Research Centre and the internal report of CSG, the price of a "one remote" terminal unit is $706.95, a "two remote" terminal unit is $3534.77, a "three remote" terminal unit is $4241.72, and the social and economic loss caused by power shortage of distribution network is 3.25 $/kWh. The annual cost of maintaining the FTUs accounts for 10% of the initial investment, the discount rate is 10%, and the planning period is 5 years.

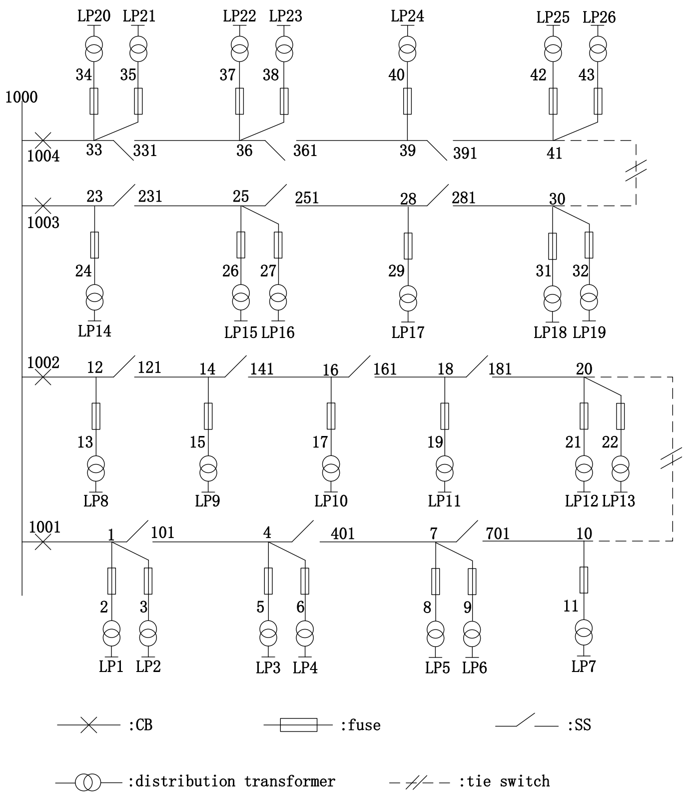

Figure 4. The Roy Billinton test system (RBTS) BUS 5 system.

Table 1. The type and average load of each load point.

Load Point No.	Load Point Type	Average Load/kW
1-2, 20, 21	Resident load	426.9
4, 6, 15, 25	Resident load	417.1
9-11, 13, 26	Resident load	321.3
5, 8, 17, 23	Industrial load	624.7
3	Government load	624.7
7, 14, 18, 22, 24	Commercial load	408.9
12, 16, 19	Office load	378.6

Table 2. The values of parameters α, β and γ of various load points.

Load Point Type	α	β	γ
Large hospital load	5	2	1
Business center load	1	2	1
Large factory load	1	5	1
Governmental agency load	1	1	4
Communication enterprise load	1	4	2
Railway system load	2	2	2
Scientific research institution load	1	1	3
Other loads	1	1	1

Table 3. The failure rate and average repair time of each element.

Element Type	Failure Rate/(times/yr)	Repair Time/(hr/times)
Line	0.03	5
Distribution transformer	0.0015	20
Fuse	0.002	3
CB	0.006	4
SS	0.006	4
Tie switch	0.002	2
Load	0.017	11

5.2. Comparative Analysis of Solving Algorithms

The iterations of the GA, DPSO, and ACO are set as 50, and the population size is set as 50. More detailed parameters of the three algorithms are summarized in Table 4. Because of the randomness of the calculation results of the intelligent algorithms, and the inaccurate prediction of deviation between the satisfactory solution and the optimal solution, 10 individual simulation runs are conducted. The box graph of the objective function values obtained from the 10 runs are shown in Figure 5. Evaluation indexes of the most satisfactory configuration scheme are summarized in Table 5, and the index results representing the optimization performances of the algorithms are presented in Table 6. In addition, the data in Tables 5 and 6 are the average results of 10 runs, where t_{con} is the average convergence time of the algorithm; n_{con} is the average convergence iterations of the algorithm; and D, SD, and RSD are the variance, standard deviation, and relative standard deviation of the objective function values of the 10 runs, respectively.

Table 4. The specific parameters of the three algorithms.

Algorithm	Parameter	Parameter Value
ACO	Pheromone decay parameter	0.1
	Heuristic information weight coefficient	2
GA	Mutation probability	0.05
	Crossover probability	0.8
DPSO	Inertia weight coefficient	2
	Cognitive acceleration constant	2
	Cooperative acceleration constant	2

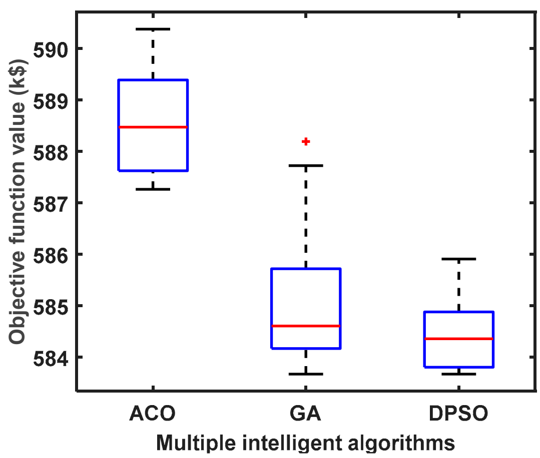

Figure 5. Box graph of calculation results of three intelligent algorithms running 10 times.

Table 5. Simulation results of three algorithms.

Intelligent Algorithm	LCC/ k$	C_{inv}/ k$	C_{mt}/ k$	C_{ens}/ k$	SAIDI/ (hr/yr.cust)	SAIFI/ (times/yr.cust)	CAIDI/ (hr/yr.cust)	ASAI/ %
ACO	588.5416	32.31	3.231	108.1784	0.4740	0.1462	3.2432	99.9946
GA	585.1960	28.42	2.842	108.6759	0.4761	0.1462	3.2574	99.9946
DPSO	584.4979	29.27	2.927	108.2814	0.4747	0.1462	3.2483	99.9946

Table 6. Optimization performance results of three algorithms.

Intelligent Algorithm	t_{con}/s	n_{con}	D	SD	RSD
ACO	0.0726	24.2	0.5691	0.7544	0.1812
GA	0.9761	18.1	1.2324	1.1101	0.2682
DPSO	0.0378	10.7	0.2628	0.5126	0.1240

It can be found from Figure 5 that GA has the worst stability with the largest difference of 10 runs. So that multiple simulation is recommended if GA is used for FTUs placement optimization. Although the stability of ACO is better than that of GA, ACO is easy to fall into local optimal solution, which is a serious drawback especially in such problems. DPSO has the best performance, with the best stability, and the closest results to the global optimal solution.

It can be seen more clearly from Table 6 that DPSO is the most stable algorithm, followed by ACO and GA. In terms of convergence speed, DPSO completes the convergence process in about 10 generations on average; ACO takes the most iterations while consumes the same solution time as DPSO, which is less than 0.1 seconds; by contrast, GA consumes the longest convergence time and has a moderate iteration number.

To sum up, DPSO is the most suitable method for the proposed FTUs placement optimization.

5.3. Comparative Analysis of Configuration Schemes

In this Section, the following two points need to be verified:

Point 1: the configuration scheme by the proposed model with the reliability constraints is better than the current planning guideline configuration scheme of "three remote" terminal units for all SSes.

Point 2: The LCC-based model for FTUs configuration optimization problem is more superior than the models built from other perspectives.

Therefore, four schemes are compared in this section, including:

Scheme 1: The proposed optimal placement scheme and multiple evaluation indexes.

Scheme 2: The suboptimal solution of the model and method proposed in this paper.

Scheme 3: The scheme that all SSs are equipped with "three remote" terminal units. The reliability indices are calculated by the reliability algorithm under the condition of DA, which is elaborated in Section 2.

Scheme 4: The model with the minimum initial investment cost as the objective function and the reliability constraints consistent with scheme 1.

Scheme 5: The model with the minimum sum of initial investment cost, maintenance cost and outage loss as the objective function, which also needs to meet the reliability constraints as same as scheme 1.

According to the algorithm performance in Section 5.2, the DPSO is used to solve the optimization models of scheme 1, 2, 4, and 5. After running the DPSO 10 times, the FTUs configuration corresponding to the minimum value of its objective function is taken as the final solution of each scheme. In addition, the number of particles is 50, the number of iterations is 50, the inertia weight is 2, the cognitive acceleration constant and cooperative acceleration constant are both 2. The placement of FTUs in scheme 1, 2, 4, 5 is illustrated in Figure 6. The evaluation indexes of each scheme's final calculation result are summarized in Table 7.

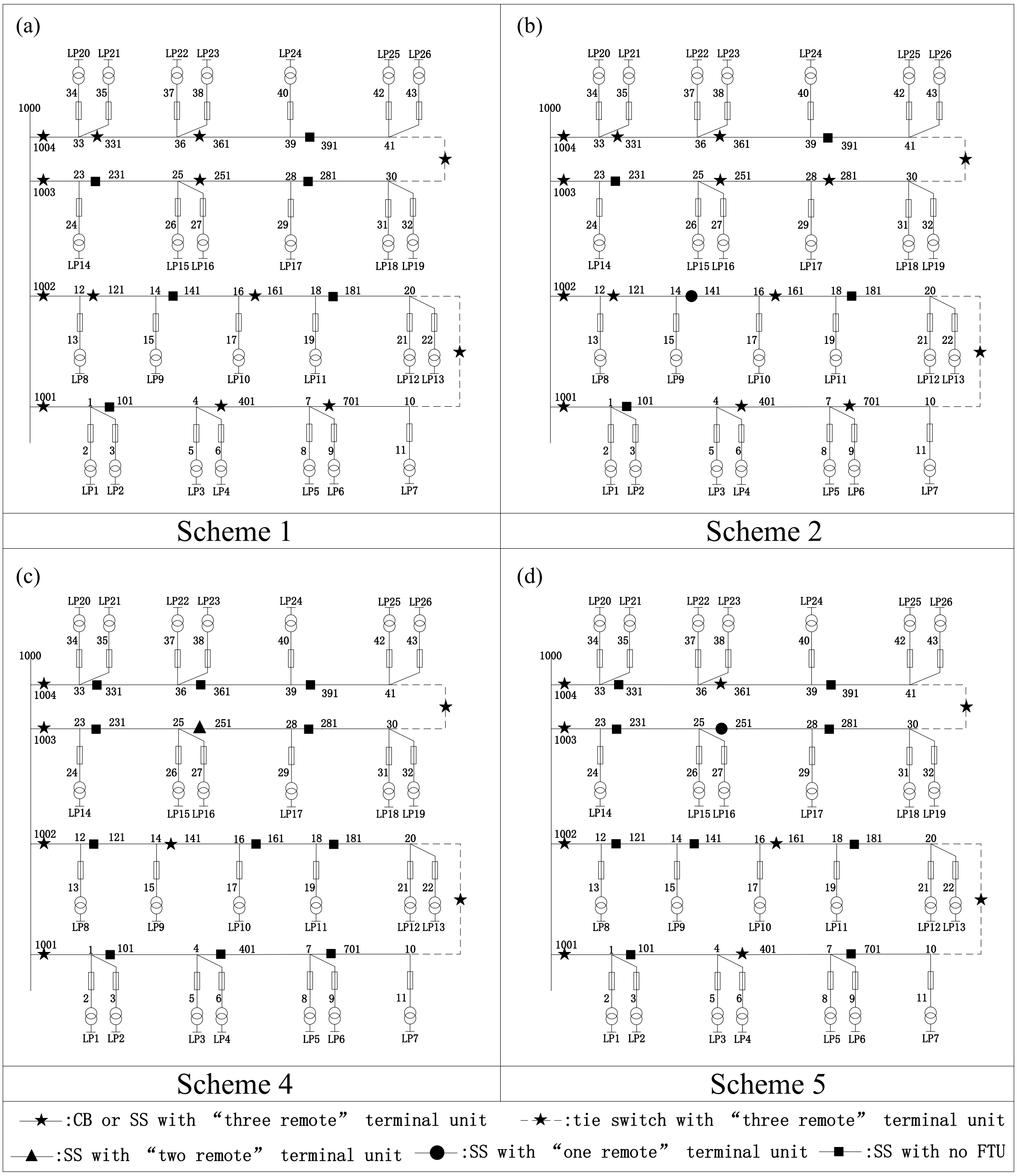

Figure 6. The placement of multiple FTUs in scheme 1, 2, 4, 5: (**a**) The placement of multiple FTUs in scheme 1; (**b**) The placement of multiple FTUs in scheme 2; (**c**) The placement of multiple FTUs in scheme 4; (**d**) The placement of multiple FTUs in scheme 5.

Table 7. Evaluation indexes of each configuration scheme.

Scheme	*LCC*/ k$	C_{inv}/ k$	C_{mt}/ k$	C_{ens}/ k$	SAIDI/ (hr/yr.cust)	SAIFI/ (times/yr.cust)	CAIDI/ (hr/yr.cust)	ASAI/ %
scheme 1	583.6701	29.69	2.969	107.9882	0.4746	0.1462	3.2470	99.9946
scheme 2	585.3152	34.64	3.464	106.8316	0.4706	0.1462	3.2196	99.9946
scheme 3	597.8852	55.14	5.514	103.1927	0.4503	0.1461	3.0812	99.9949
scheme 4	640.0358	7.78	0.778	125.8588	0.5490	0.1463	3.7560	99.9937
scheme 5	611.1294	13.43	1.343	118.3708	0.5166	0.1462	3.5347	99.9941

The most satisfactory FTUs configuration in scheme 1 shown in Figure 6 is only equipped with "three remote" terminal units, without "one remote" terminal units and "two remote" terminal units. However, it cannot be explained that it is meaningless to model and solve the placement problem of multiple FTUs. Because this result is closely related to the values of original parameters taken in the test case (such as the purchase prices of the FTUs, the outage loss per unit electricity shortage, several troubleshooting times related to the management level of the utilities, failure rate and repair time of all elements in the distribution network, etc.). This result can only reflect that with the parameters obtained from the actual research of a certain area in China in this paper, it is better to only consider "three remote" terminal units' locations than to configure three types of FTUs concurrently from the perspective of LCC. In the case of other values of the input parameters, it cannot be denied that the distribution network with multiple FTUs configurations may perform better.

It should be noted that the data in row 2 of Table 7 is different from that in row 4 of Table 5 (both are solved by DPSO), because the result in Table 7 is the optimal value of 10 simulation runs, while the result in Table 5 is the average value obtained from the 10 simulation runs.

The results of Table 7 are analyzed as follows:

(1) By comparing the calculation results of scheme 1, 2, and 3, it can be seen that:

Compared to scheme 3, the reliability indices SAIDI of the configuration scheme given in the proposed model (scheme 1) is increased by 1.458 min/yr.cust, with SAIFI almost unchanged, CAIDI increased by 9.948 min/yr.cust, and ASAI decreased by 0.0003%; however, its initial investment cost is reduced by 46.155% (25.45 k$), and its LCC is decreased by 2.378% (14.2151 k$).

This results show that although scheme 3 realizes the most reliable operation, the blind and comprehensive configuration of "three remote" terminal units is not necessarily the optimal scheme when economy and reliability are considered simultaneously with the only variable, i.e., FTUs' placement.

It can be seen that the evaluation indexes of scheme 2 is close to that of scheme 1. Therefore, the comparison results of scheme 2 and scheme 3 are similar to those of scheme 1 and scheme 3. In scheme 2, multiple FTUs are configured for the distribution network. The evaluation index of scheme 2 in Table 7 strongly shows that from the perspective of LCC, the distribution network considering multiple FTUs optimal configuration is better than configuring "three remote" terminal units blindly and widely. This verifies the significance of optimizing the configuration of feeder automation terminals in distribution network.

This conclusion is more meaningful in suburbs or rural areas without large-scale industry and commerce. The reliability requirements of distribution network in these areas are not as high as those in cities or downtown areas. The FTUs configuration scheme obtained by the proposed optimization model can not only meet the reliability constraints of the area, but also perform better in economy.

(2) By comparing the calculation results of four schemes in Table 7, it can be seen that:

The sum of outage loss and maintenance cost accounts for a large proportion, and the cost is generated every year in the whole life cycle of distribution network, which proves the superiority of terminal configuration optimization model based on the whole LCC. Therefore, it should be fully considered in the planning stage of distribution network project.

(3) By comparing the calculation results of scheme 1 and scheme 4, 5, it can be seen that:

The LCC of the planning scheme with the minimum initial investment cost (scheme 4) or the minimum sum of initial investment cost, maintenance cost and outage loss (scheme 5) as the objective function is greater than that of scheme 1, so they are not the scheme with the minimum LCC. The initial investment cost of scheme 1 is 281% (21.91 k$) and 121% (16.26 k$) higher than that of scheme 4 and scheme 5, respectively, while the annual outage loss of distribution network is reduced by 14.199% (17.87 k$) and 8.771% (10.38 k$) respectively. Such loss reduction is considerable after accumulating every year. Therefore, the initial investment cost in the early stage has a certain impact on the cost generated in the operation stage of the distribution network project. The high initial investment of FTUs may reduce the future outage loss, thus reducing the LCC of the configuration scheme.

6. Conclusions

In this paper, a mixed configuration optimization model of multiple centralized feeder automation terminal units based on LCC is established, and the reliability of distribution network under the condition of centralized feeder automation is analyzed in detail. Under the constraints of meeting the system reliability requirements, the model effectively solves the optimal FTU placement problem and provides a more targeted and elaborate solution including three types of FTUs rather than configuring "three remote" terminal units excessively. The main conclusions can be drawn as follows:

- Satisfying the reliability constraints of the distribution network means that the reliability requirement is allowed to be lower than the highest level. In this case, when the configuration of FTUs is the only variable, the mixed configuration of multiple FTUs can better coordinate the economic cost and reliability than the blind configuration of "three remote" terminal units.
- The FTU configuration scheme with the minimum initial investment cost or the minimum sum of initial investment cost, maintenance cost, and outage loss as the objective function may not be the scheme with the minimum LCC.
- The initial investment cost in the early stage has a certain impact on the cost generated in the operation stage of the distribution network project. The scheme with high initial investment of FTUs may reduce the future outage loss, thus reducing the LCC of the configuration scheme.
- Compared with GA and ACO, DPSO has better performance in solving the optimization problem of FTUs' configuration. The result solved by DPSO is closest to the global optimal solution, with a good stability and fast convergence speed. GA is a feasible option when solving planning problem which does not require high calculation speed, but multiple simulation runs are recommended due to its poor stability. In addition, ACO is not suitable here for the defects in converging to local optimum easily.

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Abbreviations

FTU	Feeder terminal unit
DA	Distribution automation
DAS	Distribution automation system
DTU	Distribution terminal unit
RMU	Ring main unit
SS	Sectionalizing switch
CSG	China Southern Power Grid Company Limited
RCS	Remote control switch
RTU	Remote terminal unit
FI	Fault indicator
LCC	Life cycle cost
SAIFI	System average interruption frequency index
SAIDI	System average interruption duration index
CAIDI	Customer average interruption duration index
ASAI	Average service unavailability index
EENS	Expected unsupplied energy

CB	Circuit breaker
FEMA	Failure Mode and Effect Analysis
RNVS	Remotely non-visual segment
MPS	Minimum patrol segment
MFS	Minimum fault segment
MFP	Main feeder point
AP	Associated path
RBTS	Roy Billinton test system
GA	Genetic algorithm
DPSO	Discrete particle swarm optimization
ACO	Ant colony optimization

Appendix A

Appendix A.1. Combination of ACO and the Model

Firstly, the switches which are considered about the configuration of FTUs are numbered. The process of solving the model by ACO is a tour that ant colony starts from the initial switch, reaches each switch in turn, and stays at the last switch. Each ant gives a path combination for the optimization problem, that is, the decision vector X of Equation (6). Each ant has a state in each switch, which corresponds to the FTU configuration decision of the switch. The path that the ant chooses when it goes from the i-th switch to the $(i + 1)$-th switch determines the state of the ant in the $i + 1$ switch. According to the Equations (1)–(5) in reference [23], the path selection is based on the probabilistic state transition rule, which is related to the length of the path (i.e., the investment cost of the decision) and the pheromone concentration on the path. After the ant colony completes the tour, the path combination given by each ant is evaluated by Equations (7)–(12). It is worth noting that the penalty function generated by constraint Equations (13)–(14) should be added to the objective function during the evaluation process. Finally, the pheromone matrix is updated by concentration volatilization and concentration enhancement according to the evaluation results. This process is repeated until the end of iteration condition is reached, and the final solution is the best one in this iterative process.

Appendix A.2. Combination of DPSO and the Model

Each particle makes a decision on this optimization problem, that is, each particle corresponds to a decision vector X of Equation (6), and the decision corresponding to the value of vector's component is consistent with that described in Section 3.1 of this paper. The velocity vector is an integer vector with the same dimension as the particle. Refer to Equations (3)–(4) in reference [24], the calculation of the velocity vector still uses the formula in the basic PSO, rounding the calculation result to get the integer vector, and then adding the velocity vector and the decision vector of the previous generation of particles to get the decision vector of the next generation of particles. In particular, it is necessary to limit the decision vector size of the next generation of particles to ensure that each component is an integer within the interval [0, 3], and for components exceeding the specified maximum value (or minimum value), it is modified to the specified maximum value (or minimum value).

Appendix A.3. Combination of GA and the Model

Generally, GA uses 0-1 encoding method. In order to make the optimization model of this paper easy to be solved and calculated, this paper uses integer encoding, so that the decision vector of Equations (6) can be directly used as the gene sequence of a chromosome. The fitness function is the objective function calculated by Equations (7)–(12). Constraint Equations (13)–(14) are added to the fitness function in the form of penalty function. The selection operator adopts roulette strategy. The crossover operator adopts single point crossover. The mutation operator selects the gene in the individual according to the mutation probability, and then randomly specifies it as another integer in the interval [0, 3]. The initial population is randomly generated, and the selection, crossover and mutation operators are repeated to update the population. In the last generation of population, the individual with the best fitness function is the solution.

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