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Optimal Placement of Fault Indicator and Sectionalizing Switch in Distribution Networks

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ABSTRACT Distribution network automation is considered by power supply companies as an effective investment strategy to improve reliability and service quality. Switching devices and protective devices play an important role in the distribution automation system (DAS). This paper presents a novel method to optimize placement of fault indicators and sectionalizing switches in distribution networks with branch lines. The objective function of the proposed method includes the total cost of fault indicators and sectionalizing switches as well as interruption cost. Among different automation equipment, this paper considers fault indicators and remote controlled switches. Besides, manual switches are taken into account since their number and location have a significant impact on the optimal placement problem. Mixed-integer linear programming is used to model the problem, and the proposed model can be solved by large-scale commercial solvers. The solution to the problem is composed of the optimal number and location of fault indicators and sectionalizing switches. The validity of the proposed method is demonstrated by relevant case studies and sensitivity analysis. Moreover, the proposed method is applied to a real distribution network to verify its practicability.

INDEX TERMS Fault indicator (FI), manual switch (MS), remote controlled switch (RCS), mixed-integer linear programming (MILP), reliability, distribution network.

I. INTRODUCTION

With the increasingly fierce competition in the power market, power supply companies enhance their competitiveness by improving reliability and service quality. Meanwhile, customers have higher requirements for reliability. The distribution network consists of a series of components, such as lines, distribution transformers, capacitors, etc. Compared with other parts of the power system, the distribution network contains more kinds and quantities of components. And the structure of the distribution network is more complicated. Therefore, faults occur more frequently in the distribution network. To improve automation level and reliability effectively, fault indicators and sectionalizing switches are placed in the distribution network by power supply companies. The placement of the fault indicator and sectionalizing switch can significantly reduce the interruption cost and improve the power system reliability. The fault indicator does not have the ability to isolate the healthy area from the faulted area by breaking the line. After a fault occurs in the distribution network, the fault indicator accelerates the fault location process and the power supply restoration process by providing the fault current information to the distribution network operation center. The interruption cost is effectively reduced, and the power system reliability is effectively improved. The sectionalizing switch can isolate the healthy area from the faulted area by breaking the line. After a fault occurs in the distribution network, the sectionalizing switch isolates the healthy area from the faulted area, and the power supply to the customer in the healthy area is restored. The number and interruption duration of customers who experience the interruption is effectively reduced. Moreover, the interruption cost is effectively reduced, and the power system reliability is effectively improved. Reliability cannot satisfy the requirements, and the investment is meager when all possible locations in the distribution network are equipped with fault

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indicators. Reliability can fulfill the requirements, and the investment is very high when all possible locations in the distribution network are fitted with sectionalizing switches. To meet the reliability requirements and reduce the investment significantly, it is necessary to optimize the placement of fault indicators and sectionalizing switches in the distribution network. Plenty of literature has studied the optimal placement of devices in the distribution network.

Reference [1] solved the feeder-switch relocation in the distribution network, and the objective function was to minimize customer interruption cost. Reference [2] studied the optimal placement of sectionalizing switches in distribution networks. The objective function was to minimize the number of sectionalizing switches, and the solution obtained had strong applicability. Switch failure has a significant impact on the switch placement problem. References [3], [4] presented several models that integrated switch failure into the sectionalizing switch placement problem. These models aimed to minimize the total cost of sectionalizing switches and the customers interruption cost. In [5], a multiobjective model was proposed to optimize the placement of sectionalizing switches and reclosers in distribution networks. The proposed model aimed to minimize the reliability investment cost and reliability indices under power flow constraints. Reference [6] also proposed a multiobjective model to optimize the configuration of sectionalizing switches and reclosers in distribution networks. In [7], [8], a multiobjective model was used to solve the optimal placement of fault management equipment problem. Fault management equipment consisted of the sectionalizing switch, recloser, and fuse. The multiobjective model minimized the total cost and reliability indices. It was worth mentioning that the total cost included fixed cost and interruption cost caused by temporary and permanent faults. Reliability indices contained system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI).

The above references have made significant contributions to the optimal placement of devices in the distribution network. However, this literature only studies the optimal placement of devices on the mainlines and ignores the influence of branch lines. With the continuous construction of the distribution network, the number of branch lines increases rapidly. Ignoring the impact of branch lines brings severe losses to power supply companies and customers. To improve automation level and reliability effectively, the optimal placement of devices needs to consider the influence of branch lines. References [9]–[11] have also made contributions to the optimal placement of devices in the distribution network.

Mathematically, the distribution network devices placement problem is summarized as a complex and combinatorial constrained optimization problem. Typically, power supply companies obtain switch placement strategies via their experience, available customer data, and other relevant information [12]. Heuristic algorithms are widely used in literature to solve the optimal placement of devices problem. Reference [13] determined the number and locations of switches through the genetic algorithm. Reference [14] adopted immune algorithm to solve the optimal placement of sectionalizing switches and aimed to minimize the reliability investment cost. Meanwhile, mathematical optimization methods, such as linear programming and mixed-integer linear programming, are also applied to solve the problem. In [15], mixed-integer linear programming was used to model the problem, and the proposed model was solved by GAMS. Reference [16] also employed mixed-integer linear programming to build the model. The solution obtained through experience is far from the global optimal solution. The disadvantage of heuristic algorithms is that computation time is long, and results are not unique in the repeated calculation. Nor can they guarantee the global optimal solution. Besides, the operation effect of these algorithms is exceptionally dependent on operator experience and parameter adjustment. Compared with heuristic algorithms, the main advantage of mathematical optimization methods is that results are unique in the repeated calculation, and the global optimal solution can be guaranteed.

References [17]–[20] tried to consider the influence of sectionalizing switch on the fault indicator placement problem. However, they did not consider the coordination relationship between fault indicator and sectionalizing switch in the fault management process. Meanwhile, the calculation of the interruption cost was not accurate. It is easy to find the difficulty in the optimal placement of fault indicator, and sectionalizing switch is to model the coordination relationship between different types of devices and calculate the interruption cost. In this paper, a mixed-integer linear programming model is established to solve the optimal placement of fault indicator and sectionalizing switch in the distribution network with branch lines. The objective function of the model is to minimize the total cost under technical and economic constraints. The total cost includes the equipment cost in conjunction with the interruption cost. The proposed method is applied to a typical test system and a real distribution network. The simulation results show the effectiveness and practicability of the proposed method. The main contributions and innovations of this paper are summarized as follows:

1) This paper proposes a mixed-integer linear programming model and solves the optimal placement of different automation equipment in the distribution network. The optimal configuration plan of equipment can guarantee high power system reliability and a high return on investment with the minimum investment cost.
2) This paper gives full consideration to the differences between different types of automation equipment and solves the problem of how to quantify and model the cooperation relationship between different kinds of automation equipment. Locations that have a significant impact on the interruption cost and the power system reliability can be found, and automation equipment is configured in these locations. The optimal

configuration plan of equipment can better guide the actual project.

3) This paper solves the problem of how to quantify and model the influence of branch lines on the configuration of automatic equipment and avoids the underestimation of reliability by manual planning. The optimal configuration plan of equipment is more practical and can improve the power system reliability better.

The rest of this paper is presented as follows. The problem statement is carried out in Section II. Section III introduces the proposed mathematical model successfully. Case studies are carried out, and simulation results are discussed in Section IV. Finally, the conclusion is given in Section V.

II. PROBLEM STATEMENT

After a fault occurs in the distribution network, the fault management process returns the system to the normal operation state. In general, a typical fault management process consists of three parts: locating the fault, isolating the fault, and restoring the power supply. Fault indicators provide information to accelerate the fault location process and the power supply restoration process. Sectionalizing switches have the ability to isolate the fault section and reduce the number and interruption duration of customers who experience the interruption. Therefore, the placement of fault indicator and sectionalizing switch in the distribution network can significantly reduce interruption cost and improve reliability.

The combination of fault indicators and sectionalizing switches can improve the automation level of the distribution network and bring considerable benefits to power supply companies. After a fault occurs in the distribution network, sectionalizing switches isolate healthy areas from the faulted area. The customer upstream to the faulted area is restored through the original path, and the customer downstream to the faulted area is restored via the alternate path connected by the tie switch. Fault indicators directly participate in the fault location process by providing the fault current information to the distribution network operation center. Furthermore, fault indicators accelerate the fault location process. According to the information provided by the fault indicator, repair crews locate and repair the fault. Then, sectionalizing switches are closed, and the power supply to the customer in the faulted area is restored. Therefore, healthy areas are composed of the upstream and downstream of the faulted area. The customer upstream to the faulted area is restored through the original path, and the interruption duration decreases from the sum of fault location time and repair time to sectionalizing switch switching time. The customer downstream to the faulted area is restored via the alternate path connected by the tie switch, and the interruption duration decreases from the sum of fault location time and repair time to tie switch transfer time. Besides, the interruption duration of the customer in the faulted area is the sum of fault location time and repair time. Because fault indicators accelerate the fault location process, both the fault location time and the interruption duration of the customer in the faulted area are reduced. The reduction of interruption duration can reduce the interruption cost and improve reliability. There are two types of sectionalizing switches: the first is called the manual switch, which implements the isolation manually. The second type is called the remote controlled switch, which performs the isolation remotely. The status of the manual switch is changed manually by repair crews, and the state of the remote controlled switch is transformed remotely by the distribution network operation center. Therefore, the remote controlled switch has a shorter switching time, which can reduce more interruption duration and interruption cost. Despite the fact remote controlled switch performs well in the fault management process, it is so expensive that it is not selected and placed preferentially by power supply companies. Power supply companies consider manual switch firstly. The remote controlled switch is chosen when the manual switch placement can not meet the relevant reliability requirements. In summary, device price and reliability requirements have a significant impact on the placement of fault indicator and sectionalizing switch.

In this paper, the objective function of the proposed method is to find the number and location of fault indicators and sectionalizing switches to minimize the total equipment cost as well as interruption cost. Reliability indices such as SAIDI, SAIFI), energy not supplied (ENS), and expected interruption cost (C_{ps}) are used widely by power supply companies to measure and quantify system operation. Nonetheless, the interruption cost can be quantified by C_{ps} in the best way since it considers the influence of network topology, customer type, number of customers, component failure rate, and interruption duration. C_{ps} can be calculated by numerical analysis method.

$$C_{ps} = \sum_{fr \in N_f} ENS_{fr} \left(h_{fr} + k_{fr} \right) \tag{1}$$

Expected interruption cost can be calculated through equation (1), which contains direct economic loss and indirect economic loss. The direct economic loss represents the reduced revenue of power supply companies due to the interruption. Indirect economic loss stands for the economic loss caused by the social impact of the interruption. Direct economic loss is measured and quantified by comprehensive electricity sale income, and comprehensive electricity sale income is equal to the difference between the electricity sale price and power supply cost. Indirect economic loss is calculated by the ratio of output value to unit electric energy consumption (ROVTUE). ROVTUE represents the social benefits that a unit of electric energy can create in a certain area at a certain time. And the ROVTUE is equal to the ratio of the gross national product (GNP) of a region or an industry to the power consumption in a year. On the other hand, equipment cost can be calculated through equation (2), which consists of the annual investment cost of equipment (C_{cap}), the annual installation cost of equipment (C_{inst}) as well as annual operation and maintenance cost of equipment ($C_{oper\&main}$).

$$I_{nv} = C_{cap} + C_{inst} + C_{oper\&main} \tag{2}$$

Annual investment cost of equipment can be calculated through formula (3) as follows:

$$C_{cap} = \sum_{fr\in N_f} \sum_{ij\in M_{fr}} \left[F^{fr,ij} C_{eq}^{SFI} + Key^{fr,ij} \left(C_{eq}^{SMS} + S\Delta C_{eq}^{SRCS}\right)\right] \tag{3}$$

The annual investment cost of equipment includes annual investment costs of fault indicators and annual investment costs of sectionalizing switches. Annual investment cost of a piece of equipment can be calculated through formula (4) as follows:

$$C_{eq}^{k} = \frac{\lambda_k (1+\lambda_k)^{N_{tk}}}{(1+\lambda_k)^{N_{tk}} - 1} C_k \tag{4}$$

The annual installation cost of equipment can be quantified via equation (5) as follows:

$$C_{inst} = \sum_{fr\in N_f} \sum_{ij\in M_{fr}} \left[F^{fr,ij} C_{inst}^{SFI} + Key^{fr,ij} \left(C_{inst}^{SMS} + S\Delta C_{inst}^{SRCS}\right)\right] \tag{5}$$

The annual installation cost of equipment also consists of annual installation costs of fault indicators and annual installation costs of sectionalizing switches. The calculation of the annual installation cost of a piece of equipment is similar to that of the annual investment cost of a piece of equipment. Annual operation and maintenance cost of equipment is defined as follows:

$$C_{oper\&main} = \sum_{fr\in N_f} \sum_{ij\in M_{fr}} \Big[F^{fr,ij} \delta_1 C_{SFI} + Key^{fr,ij} (\delta_2 + S\Delta\delta_2) \left(C_{SMS} + S\Delta C_{SRCS}\right)\Big] \tag{6}$$

In the next section, the contents described above are modeled, and a mixed-integer linear model is proposed to solve the optimal placement of fault indicator and sectionalizing switch problem.

III. MATHEMATICAL MODEL

Compared with the placement of the manual switch, the placement of the remote controlled switch can improve the automation level of the distribution network and system reliability more effectively. However, the investment cost of the remote controlled switch is much higher than that of the manual switch. To reduce the investment cost, power supply companies have the priority to choose and configure the manual switch. The automation level of the distribution network and system reliability are improved. The remote controlled switch is selected and configured when the placement of the manual switch can not meet the relevant reliability requirements. According to the above practical situation, this paper establishes a mixed-integer linear programming model to solve the optimal placement of fault indicator and sectionalizing switch in the distribution network with branch lines. The proposed model considers both the manual switch and the remote controlled switch. The proposed model has the priority to choose the fault indicator and the manual switch, and the optimal configuration plan of equipment can be obtained. The fault indicator and the remote controlled switch are selected when the placement of the fault indicator and the manual switch can not meet the relevant reliability requirements. The optimal configuration plan of equipment can be obtained. Meanwhile, there is a significant gap in the economic level of different power supply regions. Because of finance and other reasons, the economically backward power supply area can only be equipped with fault indicators and manual switches to improve the automation level of the distribution network and meet the reliability requirements. Due to finance and other reasons, the economically developed power supply area can be equipped with fault indicators and remote controlled switches to improve the automation level of the distribution network and meet the reliability requirements. The proposed model also takes into account the above actual situation. In the proposed model, the binary decision variable S can control the type of sectionalizing switch. When S is equal to 0, the fault indicator and the manual switch are chosen and configured. When S is equal to 1, the fault indicator and the remote controlled switch are selected and configured.

A. OBJECTIVE FUNCTIONS

There are some locations in the distribution network that have a significant impact on the interruption cost and the power system reliability. When these locations are equipped with the equipment, the interruption cost can be effectively reduced, and the power system reliability can be effectively improved. Compared with the above locations, the other locations of the distribution network are those that have no significant influence on the interruption cost and the power system reliability. When these locations are equipped with the equipment, the interruption cost can not be effectively reduced, and the power system reliability can not be effectively improved. In this paper, the optimal configuration quantity and location of equipment can be obtained through the proposed model. Meanwhile, the optimal configuration location of equipment obtained by the proposed model is the location that has a significant impact on the interruption cost and the power system reliability. Actually, the objective function of the proposed method is a multi-objective function. The multi-objective function includes two single-objective functions. The first single-objective function is to minimize the equipment cost, and the second single-objective function is to minimize the interruption cost. This paper uses the weighting factor method to solve the multi-objective optimization problem and minimize the total cost. Furthermore, this paper assumes that the weighting factor for both costs is one. The equipment optimization configuration

$$
\begin{aligned}
&MinC_{total} \\
&= I_{nv} + C_{ps} \\
&= \sum_{fr \in N_f} \sum_{ij \in M_{fr}} \left[F^{fr,ij} C_{eq}^{SFI} + Key^{fr,ij} \left(C_{eq}^{SMS} + S\Delta C_{eq}^{SRCS} \right) \right] \\
&\quad + \sum_{fr \in N_f} \sum_{ij \in M_{fr}} \left[F^{fr,ij} C_{inst}^{SFI} + Key^{fr,ij} \left(C_{inst}^{SMS} + S\Delta C_{inst}^{SRCS} \right) \right] \\
&\quad + \sum_{fr \in N_f} \sum_{ij \in M_{fr}} \Big[F^{fr,ij} \delta_1 C_{SFI} \\
&\quad + Key^{fr,ij} \left(\delta_2 + S\Delta\delta_2 \right) \left(C_{SMS} + S\Delta C_{SRCS} \right) \Big] \\
&\quad + \sum_{fr \in N_f} ENS_{fr} \left(h_{fr} + k_{fr} \right)
\end{aligned} \tag{7}
$$

plan obtained by the proposed method minimizes the interruption cost. Therefore, the optimal configuration location of equipment obtained by the proposed method is the location that has a significant impact on the interruption cost and the power system reliability. The placement of fault indicator and sectionalizing switch in the distribution network is one of the effective measures to reduce interruption cost and improve reliability. Meanwhile, the placement of new equipment increases the equipment cost. The objective function of the proposed approach is to minimize the total cost, which consists of equipment cost and interruption cost. The objective function can be expressed by the formula (7).

According to the following assumptions, the objective function is minimized:

1) Every feeder is operated as a radial feeder, and the tie switch is configured at the end of the mainline of every feeder.
2) Section switches and fault indicators do not malfunction.
3) All faults are permanent.
4) All faults belong to first-order failure.
5) Ignoring line impedance.

B. CONSTRAINTS

The decision variables of the proposed model are the type and location of equipment. Binary decision variables are shown as follows:

$$
F^{fr,ij} = \begin{cases} 1, & \text{fault indicator is configured on line } ij \text{ in feeder } fr \\ 0, & \text{fault indicator is not configured on line } ij \text{ in feeder } fr \end{cases}
$$

$$
S = \begin{cases} 1, & \text{selecting remote controlled switch} \\ 0, & \text{selecting manualswitch} \end{cases}
$$

$$
Key^{fr,ij} = \begin{cases} 1, & \text{sectionalizing switch is configured on line } ij \text{ in feeder } fr \\ 0, & \text{sectionalizing switch is not configured on line } ij \text{ in feeder } fr \end{cases}
$$

According to the problem statement, the placement of equipment can effectively reduce the interruption duration and energy not supplied. The sectionalizing switch reduces the interruption duration and energy not supplied by isolating healthy areas from the faulted area. The coordination of tie switch and sectionalizing switch reduces the interruption duration and energy not supplied. The fault indicators reduce the interruption duration and energy not supplied by accelerating the fault location process. Compared with the fault indicator, the sectionalizing switch reduces the interruption duration and energy not supplied more. After the feeder is configured with equipment, the energy not supplied can be calculated by the formula (8).

$$
ENS_{fr} = ENS_{fr}^0 - ENS_{fr}^1 - ENS_{fr}^2 - ENS_{fr}^3 \tag{8}
$$

In equation (8), ENS_{fr} represents the energy not supplied of the feeder fr. ENS_{fr}^0 represents the energy not supplied of the feeder fr when no equipment is configured on the feeder fr. ENS_{fr}^1 represents the reduction of energy not supplied caused by sectionalizing switches that are configured on the feeder fr. ENS_{fr}^2 defines the reduction of energy not supplied caused by tie switch that is configured on the feeder fr. ENS_{fr}^3 expresses the reduction of energy not supplied caused by fault indicators that are configured on the feeder fr. ENS_{fr}^0 is defined as follows:

$$
ENS_{fr}^0 = P_{fr} \lambda_{fr} T \tag{9}
$$

When no equipment is configured on the feeder fr, a fault occurs anywhere on the feeder fr, and all customers of feeder fr experience interruption. After the fault is located and repaired by repair crews, the power supply to all customers of the feeder fr is restored. ENS_{fr}^1 is calculated through formula (10).

$$
ENS_{fr}^1 = \sum_{l \in S_{fr}} P_{up-l} \lambda_l \left(T - T_1 - S\Delta T_1 \right) \tag{10}
$$

The sectionalizing switch can reduce energy not supplied effectively. The fault occurs in the mainline of the feeder fr. After the fault management process is completed, the faulted area is isolated by sectionalizing switches, and the customer upstream to the faulted area is restored through the original path. The fault occurs in the branch line of the feeder fr, and there is no sectionalizing switch between the fault point and the mainline. After the fault management process is completed, the faulted area is isolated by sectionalizing switches, and the customer upstream to the faulted area is restored through the original path. In the above cases, the interruption duration of the customer upstream to the faulted area decreases from the sum of fault location time and repair time to sectionalizing switch switching time. And the energy not supplied of the feeder fr is reduced. The fault occurs in the branch line of the feeder fr, and there are sectionalizing switches between the fault point and the mainline. After the fault management process is completed, the faulted area is isolated by sectionalizing switches, and the customers in the fault section to the end of the branch line experience interruption. The remaining customers of the feeder fr are restored through the original path, and the interruption duration of these customers also decreases from the sum of fault location time and repair time to sectionalizing switch switching time. It is worth mentioning that the alternate path is not connected by the tie switch. ENS_{fr}^{2} is defined as follows:

$$ENS_{fr}^{2} = \sum_{l \in S_{fr}} P_{down-l} \lambda_l \left(T - T_2\right) \xi_l \tag{11}$$

The coordination of tie switch and sectionalizing switch can reduce energy not supplied significantly. The fault occurs in the mainline of the feeder fr. After the fault management process is completed, the faulted area is isolated by sectionalizing switches, and the customer downstream to the faulted area is restored via the alternate path connected by the tie switch. The fault occurs in the branch line of the feeder fr, and there is no sectionalizing switch between the fault point and the mainline. After the fault management process is completed, the faulted area is isolated by sectionalizing switches, and the customer downstream to the faulted area is restored through the alternate path connected by the tie switch. In the above cases, the interruption duration of the customer downstream to the faulted area decreases from the sum of fault location time and repair time to tie switch transfer time. And the energy not supplied of the feeder fr is reduced. The fault occurs in the branch line of the feeder fr, and there are sectionalizing switches between the fault point and the mainline. As mentioned earlier, the alternate path is not connected by the tie switch, and the energy not supplied of the feeder fr is not reduced by the tie switch.

The proposed method has considered the probability is different for the failures in different positions, which has a great impact on the economic assessment. In the proposed model, λ_l represents the failure rate of the section l. Since the statistical time is one year, the failure rate of the section l represents the failure number of the section l within one year. When the section l is located in the mainline, the failure number of the section l within one year includes the failure number of the mainline contained in the section l within one year and the failure number of distribution transformers contained in the section l within one year. When the section l is located in the branch line, the failure number of the section l within one year includes the failure number of the branch line contained in the section l within one year and the failure number of distribution transformers contained in the section l within one year. When the section l is located at both the mainline and branch line, the failure number of the section l within one year includes the failure number of lines contained in the section l within one year and the failure number of distribution transformers contained in the section l within one year. The failure number of lines contained in the section l within one year includes the failure number of the mainline contained in the section l within one year and the failure number of the branch line contained in the section l within one year. The failure number of distribution transformers contained in the section l within one year includes the failure number of distribution transformers contained in the mainline within one year and the failure number of distribution transformers contained in the branch line within one year, and both the mainline and branch line belong to the section l. When the equipment configuration plan of the feeder fr is determined, the section of the feeder fr is determined. The failure rate of each section on the feeder fr is also determined and represented by λ_l. The energy not supplied of the feeder fr can be calculated through the formula (8)-(12). Meanwhile, the expected interruption cost of the feeder fr can be calculated through the formula (1). It is worth mentioning that when the equipment configuration plan of the feeder fr is different, the section of the feeder fr is different. The failure rate of each section on the feeder fr is different, so is λ_l. The energy not supplied of the feeder fr is different, and the expected interruption cost of the feeder fr is also different. In Monte Carlo simulation, the failure rate of the section l is obtained by probability statistics. In the method proposed in this paper, the failure rate of the section l is obtained from historical data. Since the statistical time is one year, the failure rate of the section l represents the failure number of the section l within one year. The failure number of the section l within one year includes the failure number of lines contained in the section l within one year and the failure number of distribution transformers contained in the section l within one year. Both the failure number of lines contained in the section l within one year and the failure number of distribution transformers contained in the section l within one year are obtained from historical data. Compared with Monte Carlo simulation, the failure rate of the section l and the reliability index obtained by the proposed method are more practical and accurate. It is worth mentioning that the proposed method assumes the fault is first-order and permanent. These assumptions make it easier to calculate the failure rate of the section l and the reliability index. In fact, the fault may also be multi-order or temporary. The proposed method ignores the multi-order fault and the temporary fault. ENS_{fr}^{3} is defined as follows:

$$ENS_{fr}^{3} = P_{fr} \lambda_{fr} \left(1 - \frac{L_{\max}}{L_{fr}}\right) T_3 \tag{12}$$

The coordination between fault indicator, sectionalizing switch, and tie switch can reduce the fault location time and the energy not supplied of the feeder fr. Based on relevant policies and technical regulations of power supply companies, both the maximum number of available fault indicators for installation and the maximum number of available sectionalizing switches for installation are imposed. The number of installed fault indicators and the number of installed sectionalizing switches are not allowed to exceed the proposed maximum number. The constraints are expressed as follows:

$$\sum_{fr \in N_f} \sum_{ij \in M_{fr}} F^{fr,ij} \le N_{af} \tag{13}$$

$$\sum_{fr \in N_f} \sum_{ij \in M_{fr}} Key^{fr,ij} \le N_{as} \tag{14}$$

Power supply companies face a series of financial problems and budget problems, and the investment cost of equipment is limited. Both the investment cost of installed fault indicators and the investment cost of installed sectionalizing switches are not allowed to exceed the proposed maximum investment cost. The constraints are defined as follows:

$$\sum_{fr\in N_f}\sum_{ij\in M_{fr}} F^{fr,ij}C_{SFI} \leq C_{b1} \tag{15}$$

$$\sum_{fr\in N_f}\sum_{ij\in M_{fr}} Key^{fr,ij}\left(C_{SMS} + S\Delta C_{SRCS}\right) \leq C_{b2} \tag{16}$$

To effectively enhance competitiveness in the power market, power supply companies have new requirements for system reliability. In this paper, the average service availability index (ASAI) is used to measure and quantify system reliability. For ensuring the reliability of the studied area and each feeder in the studied area satisfy the reliability requirements, the following constraints are considered.

$$SAIDI = \frac{ENS}{P} \tag{17}$$

$$ASAI = 1 - \frac{1}{8760}SAIDI \geq \delta \tag{18}$$

Depending on relevant policies, technical regulations, and historical experience, equipment is allocated in some special locations, even if the return on investment is meager. This situation can be described by the following constraints.

$$F^{fr,ij} = 1 \quad (fr, ij) \in MI_1 \tag{19}$$

$$Key^{fr,ij} = 1 \quad (fr, ij) \in MI_2 \tag{20}$$

At the same time, equipment is not allocated in some particular locations, even if the return on investment is very high. The mathematical expressions are defined as follows:

$$F^{fr,ij} = 0 \quad (fr, ij) \in MNI_1 \tag{21}$$

$$Key^{fr,ij} = 0 \quad (fr, ij) \in MNI_2 \tag{22}$$

The configuration position of the fault indicator is different from that of the sectionalizing switch. Generally, the fault indicator is configured at the end of the mainline and on the normal branch line. The sectionalizing switch is configured on the mainline except for the end and the important branch line. The above equipment configuration principles can also be expressed by constraints (19)-(22). It is worth mentioning that the constraints (19)-(22) can simplify the optimization placement problem. In this paper, the line impedance is ignored, and distribution networks are modeled as a group of linear equations. Furthermore, the voltage of each node is the same. The constraints regarding the distribution network are modeled as follows:

$$\begin{cases} \sum\limits_{i\in u_{fr}(j)} P_{fr,ij} = \sum\limits_{k\in v_{fr}(j)} P_{fr,jk} + P_{fr,jD} \\ \sum\limits_{i\in u_{fr}(j)} Q_{fr,ij} = \sum\limits_{k\in v_{fr}(j)} Q_{fr,jk} + Q_{fr,jD} \end{cases} \tag{23}$$

IV. CASE STUDY

In this section, the proposed model is applied to a test network and a real distribution network. The test network is the RBTS-Bus 4 typical network, and the actual distribution network is the medium voltage distribution network of Zhongshan.

In the simulation calculation, the investment cost of a fault indicator, manual switch, and remote controlled switch is \$436, \$4360, and \$17440, respectively. The installation cost of a fault indicator, manual switch, and remote controlled switch is \$26, \$131 and \$145, respectively. The annual operation and maintenance cost scaling factor of fault indicator, manual switch, and remote controlled switch is 4%. The discount rate and economic life period of fault indicator, manual switch, and remote controlled switch are 5% and 15 years, respectively. The switching time of manual switch and remote controlled switch is 0.4h and 0.01h, respectively. The above data are all from [21], and ASAI is assumed to be no less than 0.999900.

A. MODEL IMPLEMENTATION AND SOLVING

In the SPYDER environment, the model introduced in section III is coded by PYTHON language and solved via GUROBI 8.1.0 solver. The processor model is Intel(R) Core(TM) i7-8700 CPU @ 3.20GHz. SPYDER is the integrated development environment (IDE) for the PYTHON language. GUROBI is an optimization solver with excellent performance, which can solve mixed-integer linear models effectively.

B. RBTS-BUS 4

The proposed model is applied to the RBTS-Bus 4 test system, and the test system is shown in Figure 1. This classical test system is widely used in equipment configuration research [4], [15], [22]–[26]. The test network is composed of 38 load points, 67 overhead lines, 3 tie switches, and 7 circuit breakers. The failure rate of the overhead line is 0.065 f/yr.km, and the remaining data of the test network can be found in [27], [28]. The results obtained in different cases are shown in Table 1. The first line presents the results obtained in case I. Case I does not consider the configuration of fault indicators and sectionalizing switches. In the meantime, this case serves as the base case and compares it with the rest. The second line presents the results obtained in case II, which are also the results obtained by the proposed method in this paper. Case II considers the simultaneous placement of fault indicators and sectionalizing switches. According to the results obtained in case II, the simultaneous placement of the fault indicator and manual switch can satisfy the reliability requirement. Moreover, there is no need to study the simultaneous placement of the fault indicator and remote controlled switch in the test network. The case I has the highest interruption cost and the lowest reliability. It is due to the fact that the distribution network is not equipped with fault indicators and sectionalizing switches to reduce the interruption duration

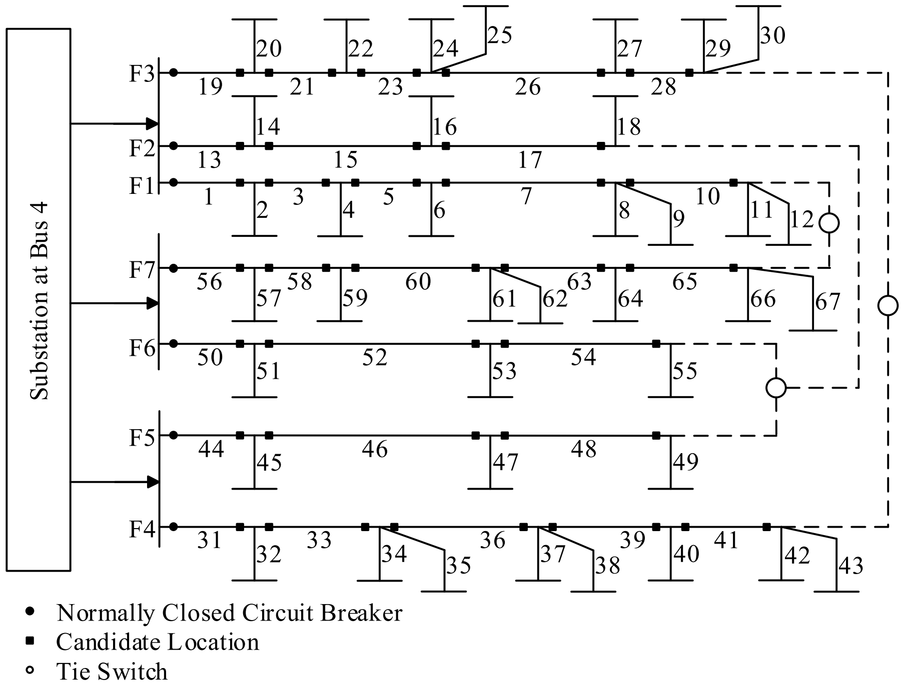

FIGURE 1. RBTS-Bus 4 test system.

TABLE 1. The number of devices and cost in different cases.

Case	Number of devices		Cost [k$]			ASAI
	FI	MS	I_{nv}	C_{ps}	C_{total}	
Case I	---	---	---	183.76	183.76	0.999817
Case II	2	11	8.13	72.54	80.67	0.999928

of customers and interruption cost. Simultaneous placement of fault indicator and manual switch in the test network reduces the interruption duration of customers and interruption cost significantly. Compared with the case I, the interruption cost obtained in case II decreases from k$183.76 to k$72.54 and the total cost obtained in case II decreases from k$183.76 to k$80.67. In the meantime, the reliability is improved, and the average service availability index rises from 0.999817 to 0.999928.

The method proposed in this paper is used to solve the optimal placement of the fault indicator and sectionalizing switch in the test network. And the results obtained by the proposed method are compared with those obtained by the existing method. Table 2 and Table 3 present the comparison results. The equipment configuration plan obtained by the proposed method requires less equipment and does not need to configure remote controlled switches. Meanwhile, the equipment configuration plan obtained by the proposed method has a lower total cost. The total cost decreases from k$92.01 to k$80.67, with a reduced rate of 12.32%. In the equipment configuration plan obtained by the proposed method, the equipment is configured in the locations that have a significant impact on the interruption cost and the power system reliability. There are some locations in the distribution network that have a significant impact on the interruption cost and the power system reliability. When these locations are equipped with the equipment, the interruption cost can be effectively reduced, and the power system reliability can be effectively improved. In the equipment configuration plan obtained by the existing method, the equipment is configured in the locations that have no significant influence on the interruption cost and the power system reliability. Compared with the locations that have a significant impact on the interruption cost and the power system reliability, the other locations of the distribution network are those that have no significant influence on the interruption cost and the power system reliability. When these locations are equipped with the equipment, the interruption cost can not be effectively reduced, and the power system reliability can not be effectively improved. To sum up, the proposed method can better solve the optimal placement of fault indicators and sectionalizing switches in the distribution network.

To evaluate the impact of different key parameters on the solution to the optimal placement of fault indicator and sectionalizing switch and several sensitivity analyses are performed on the test system. The optimal placement of fault indicator and sectionalizing switch requires the line failure rate, and the line failure rate is generally obtained through investigation or estimation. However, the line failure rate obtained by these methods is not accurate. Next, the influence of the line failure rate on the solution to the optimal placement of fault indicator and sectionalizing switch is discussed. The line failure rate used in case II is increased and reduced by

TABLE 2. The equipment configuration plan obtained by different methods.

Method	Number of devices			Cost [k$]			ASAI
	FI	MS	RCS	I_{nv}	C_{ps}	C_{total}	
New method	2	11	0	8.13	72.54	80.67	0.999928
Existing method[20]	4	13	3	18.43	73.58	92.01	0.999927

TABLE 3. Optimal location of equipment obtained by different methods.

Method	Optimal location (Line, Side)		
	FI location	MS location	RCS location
New method	(10,B) (41,B)	(3,B) (7,B) (15,B) (21,B) (26,B) (33,B) (39,B) (46,B) (52,B) (58,B) (63,B)	---
Existing method [20]	(5,B) (36,B) (41,B) (54,E)	(3,B) (7,B) (15,B) (17,B) (21,B) (23,B) (33,B) (39,B) (44,E) (48,B) (50,E) (58,B) (65,B)	(10,B) (28,B) (54,B)

Note: B represents the beginning of the line, E represents the end of the line.

TABLE 4. The influence of line failure rate on the solution to the optimal placement of equipment.

Failure rate changes	Number of devices		Cost [k$]		
	FI	MS	I_{nv}	C_{ps}	C_{total}
+60%	5	14	10.52	95.44	105.96
+30%	4	12	9.00	85.30	94.30
---	2	11	8.13	72.54	80.67
-30%	1	9	6.60	65.27	71.87
-60%	0	7	5.08	58.14	63.22

TABLE 5. The influence of the lower limit of ASAI on the solution to the optimal placement of equipment.

The lower limit of ASAI	Number of devices			Cost [k$]		
	FI	MS	RCS	I_{nv}	C_{ps}	C_{total}
0.999810	1	5	0	3.70	75.77	79.47
0.999855	2	8	0	5.95	74.01	79.96
0.999900	2	11	0	8.13	72.54	80.67
0.999945	1	0	7	21.35	66.71	88.06
0.999990	3	0	13	38.91	58.52	97.43

30% and 60%. The results obtained by different line failure rates are shown in Table 4. From the simulation results, it can be found that the reliability decline when the line failure rate increases. To meet the reliability requirement, the number of fault indicators and sectionalizing switches increases with the increase of the line failure rate. In the meantime, the equipment cost, interruption cost, and total cost also increase. In summary, the line failure rate has a significant impact on the solution to the optimal placement of fault indicator and sectionalizing switch.

With the rapid development of society and the economy, customers and power supply companies have higher requirements for reliability. And the lower limit of ASAI is raised. In the following, the influence of the lower limit of ASAI on the solution to the optimal placement of fault indicator and sectionalizing switch is studied. The lower limit of ASAI used in case II is increased from 0.999810 to 0.999990. The simulation results are presented in Table 5. With the improvement of the lower limit of ASAI, the number of fault indicators and manual switches, and the total cost increase. When the lower limit of ASAI reaches a certain value, the optimal placement of fault indicator and manual switch can not meet the reliability requirement. To satisfy the reliability requirement, fault indicator and remote controlled switch are configured. As the lower limit of ASAI is further improved, the number of fault indicators and remote controlled switches, and the total cost also increase. It is worth mentioning that the application of the remote controlled switch significantly increases the equipment cost. To sum up, the lower limit of ASAI reflects on the solution to the optimal placement of fault indicator and sectionalizing switch dramatically.

C. MEDIUM VOLTAGE DISTRIBUTION NETWORK OF ZHONGSHAN

To verify the practicability of the proposed method, the proposed method is applied to the medium voltage distribution network of Zhongshan. Zhongshan is a commercial city, which requires high reliability. As one of the effective measures to improve the reliability, distribution network automation has gradually attracted the attention of power supply companies. The distribution network of Zhongshan consists of 380V network, 10kV network, and 110kV network. The total length of medium voltage distribution network lines is 10067.47km, including 6204.65km of cable lines and 3862.82km of overhead lines. Moreover, the medium voltage distribution network has 28763 distribution transformers (10/0.38kv). The high voltage distribution network has 83 transformer substations (110/10kv). The distribution network studied is shown in Figure 2. The system contains 147 distribution transformers. All distribution transformers

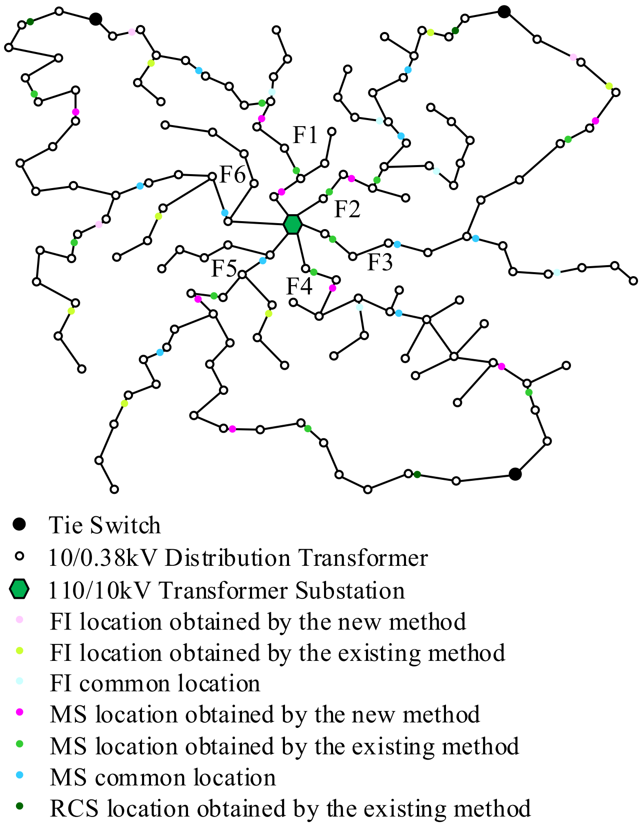

FIGURE 2. Single line diagram of the Zhongshan distribution network.

TABLE 6. The number of devices and cost in different cases.

Case	Number of devices		Cost [k$]			ASAI
	FI	MS	I_{nv}	C_{ps}	C_{total}	
Case I	---	---	---	96.27	96.27	0.999733
Case II	8	19	14.37	35.39	49.76	0.999902

are powered by six feeders numbered F1 to F6. All feeders originate from the same transformer substation (110/10kv), and all feeders are the overhead line. The failure rate of the overhead line is 0.07 f/yr.km. The remaining data on the distribution network can be found in [21].

To obtain the optimal number and location of fault indicators and sectionalizing switches, and the method proposed in this paper is applied to the Zhongshan distribution network. Different cases are simulated, and the results are presented in Table 6. The first line shows the results obtained in case I. Case I does not consider the placement of fault indicators and sectionalizing switches. The second line shows the results obtained in case II, which are also the results obtained by the proposed method. Case II considers the simultaneous placement of fault indicators and sectionalizing switches. According to the results obtained in case II, the simultaneous placement of the fault indicator and manual switch can satisfy the reliability requirement. Moreover, there is no need to

TABLE 7. The reduction of energy not supplied caused by the equipment configured on the branch lines and the decreasing proportion.

Feeder	The reduction of energy not supplied [MWh]	Initial energy not supplied [MWh]	Percentage
F1	2.93	8.83	33.18%
F2	3.89	12.67	30.70%
F3	3.64	11.31	32.18%
F4	0.76	2.41	31.54%
F5	3.02	9.37	32.23%
F6	2.83	9.41	30.07%
Total	17.07	54.00	31.61%

TABLE 8. The reduction of interruption cost caused by the equipment configured on the branch lines and the decreasing proportion.

Feeder	The reduction of interruption cost [k$]	Initial interruption cost [k$]	Percentage
F1	5.22	15.75	33.14%
F2	6.93	22.58	30.69%
F3	6.49	20.15	32.21%
F4	1.35	4.30	31.40%
F5	5.39	16.71	32.26%
F6	5.04	16.78	30.04%
Total	30.42	96.27	31.60%

study the simultaneous placement of the fault indicator and remote controlled switch in the network. Compared with the case I, case II has lower interruption cost and total cost. In the meantime, case II has higher reliability. The reason is that the placement of fault indicators and sectionalizing switches reduces the interruption duration of customers and interruption cost significantly. The total cost of the case I and case II is k\$96.27 and k\$49.76, respectively. Also, the total cost of case II is reduced by 48.31%. In case 2, fault indicators and manual switches are configured on the mainlines and branch lines. Fault indicators and manual switches configured on the branch lines reduce the energy not supplied and interruption cost dramatically. The reduction of the energy not supplied and interruption cost is presented in Table 7 and Table 8, respectively. The energy not supplied is decreased by 17.07 MWh, with a reduced rate of 31.61%. Moreover, the interruption cost is reduced by k\$30.42, with a reduced rate of 31.60%. In conclusion, fault indicators and sectionalizing switches that are configured on the branch lines can reduce the energy not supplied and interruption cost effectively. It is worth mentioning that the initial energy not supplied represents the energy not supplied when the distribution network is not equipped with fault indicators and sectionalizing switches. And the initial interruption cost represents the interruption cost when the distribution network is not equipped with fault indicators and sectionalizing switches.

Finally, both the proposed method and the existing method are applied to the Zhongshan distribution network. Figure 2 presents the optimized access location of components obtained by different methods, and Table 9 presents the relevant simulation results. It is not difficult to find that

TABLE 9. The equipment configuration plan obtained by different methods.

Method	Number of devices			Cost [k$]			ASAI
	FI	MS	RCS	I_{nv}	C_{ps}	C_{total}	
New method	8	19	0	14.37	35.39	49.76	0.999902
Existing method[20]	12	22	3	25.54	35.64	61.18	0.999901

equipment configuration plans obtained by the two methods can make the reliability meet the requirement, and the equipment configuration plan obtained by the proposed method can improve the reliability more effectively. Meanwhile, the equipment configuration plan obtained by the proposed method requires less equipment and has a lower total cost. The total cost decreases from k$61.18 to k$49.76, with a reduced rate of 18.67%. With the increasingly fierce competition in the power market, power supply companies pay more attention to investment benefits. The goal of power supply companies is to make reliability satisfy the requirement, and the total cost less. Therefore, the power supply company selects the equipment configuration plan obtained by the proposed method. In summary, the method proposed in this paper can better solve the optimal placement of fault indicators and sectionalizing switches in the actual distribution network.

V. CONCLUSION

In this paper, a mixed-integer linear programming model is proposed to find out the number and location of fault management equipment of the distribution network. Fault management equipment includes fault indicator, manual switch, and remote controlled switch. A mathematical optimization method is adopted to improve the reliability and service quality of the distribution network. The objective function is to minimize the total cost under technical and economic constraints. The fault indicator and remote controlled switch will be configured when the configuration of the fault indicator and manual switch can not satisfy the reliability requirements. Compared with other methods, the proposed method ensures the global optimum solution. The proposed method can effectively solve the optimal configuration of fault management equipment in the distribution network with branch lines. It is worth mentioning that the reasonable configuration of fault management equipment in branch lines can dramatically reduce interruption cost and improve reliability. The proposed method is applied to the RBTS-Bus 4 typical test system and the medium voltage distribution network of Zhongshan. The simulation results reveal the superiorities of the proposed method. Besides, the influence of line failure rate and ASAI lower limit on the optimal configuration of fault management equipment is studied through sensitivity analysis.

Finally, as more and more distributed generations(DG) are connected to the distribution network, the optimal configuration of switching devices and protective devices considering the impact of distributed generations will become the future research direction.

APPENDIX

NOMENCLATURE

INDICES AND SETS

- fr, N_f — Index and set of feeders.
- ij, M_{fr} — Index and set of lines on the feeder fr.
- l, S_{fr} — Index and set of sections on the feeder fr.
- i, $u_{fr}(j)$ — Index and the head node set of lines with j as the end node on the feeder fr.
- k, $v_{fr}(j)$ — Index and the end node set of lines with j as the head node on the feeder fr.
- MI_1 — Set of lines in which fault indicator must be installed.
- MI_2 — Set of lines in which sectionalizing switch must be installed.
- MNI_1 — Set of lines in which fault indicator must not be installed.
- MNI_2 — Set of lines in which sectionalizing switch must not be installed.

PARAMETERS AND CONSTANTS

- C_{eq}^{SFI} — Annual investment cost of a fault indicator.
- C_{eq}^{SMS} — Annual investment cost of a manual switch.
- ΔC_{eq}^{SRCS} — The difference between the annual investment cost of a remote controlled switch and a manual switch.
- C_{inst}^{SFI} — The annual installation cost of a fault indicator.
- C_{inst}^{SMS} — The annual installation cost of a manual switch.
- ΔC_{inst}^{SRCS} — The difference between the annual installation cost of a remote controlled switch and a manual switch.
- δ_1 — Annual operation and maintenance cost scaling factor of the fault indicator.
- δ_2 — Annual operation and maintenance cost scaling factor of the manual switch.
- $\Delta\delta_2$ — The difference between the annual operation and maintenance cost scaling factor of the remote controlled switch and manual switch.
- C_{SFI} — Investment cost of a fault indicator.
- C_{SMS} — Investment cost of a manual switch.
- ΔC_{SRCS} — The difference between the investment cost of a remote controlled switch and a manual switch.
- h_{fr} — Comprehensive electricity sale income of the feeder fr.
- k_{fr} — The ratio of output value to unit electric energy consumption (ROVTUE) of the feeder fr.
- P — Total active power load.

P_{fr}	Total active power load of the feeder fr.
$P_{fr,jD}$	The active power load of the node j on the feeder fr.
$Q_{fr,jD}$	The reactive power load of the node j on the feeder fr.
λ_{fr}	The total failure rate of the feeder fr.
T	Interruption duration includes fault location time and fault repair time.
T_1	Switching time of the manual switch.
ΔT_1	The difference between the switching time of remote controlled switch and manual switch.
T_2	Transfer time of tie switch.
T_3	Fault location time.
L_{fr}	Length of the feeder fr.
N_{af}	The maximum number of available fault indicators for installation.
N_{as}	The maximum number of available sectionalizing switches for installation.
C_{b1}	Maximum investment cost of fault indicators.
C_{b2}	Maximum investment cost of sectionalizing switches.
δ	The lower limit of ASAI provided by the power supply company.

FUNCTIONS AND VARIABLES

C_{total}	Total cost.
I_{nv}	Equipment cost.
C_{cap}	Annual investment cost of equipment.
C_{inst}	Annual installation cost of equipment.
$C_{oper\&main}$	Annual operation and maintenance cost of equipment.
C_{ps}	Expected interruption cost.
C_{eq}^k	Annual investment cost of a piece of equipment k.
λ_k	The discount rate for the equipment k.
N_{tk}	The economic life period of the equipment k.
C_k	Investment cost of a piece of equipment k.
$F^{fr,ij}$	Binary decision variable.
S	Binary decision variable.
$Key^{fr,ij}$	Binary decision variable.
ξ_l	Binary decision variable; 1 if the section l is on the mainline of feeder fr, 0 otherwise.
ENS	Energy not supplied.
ENS_{fr}	Energy not supplied of the feeder fr.
ENS_{fr}^0	The energy not supplied of the feeder fr while no equipment is configured on the feeder fr.
ENS_{fr}^1	The reduction of energy not supplied caused by sectionalizing switches that are configured on the feeder fr.
ENS_{fr}^2	The reduction of energy not supplied caused by tie switch, which is configured on the feeder fr.
ENS_{fr}^3	The reduction of energy not supplied caused by fault indicators that are configured on the feeder fr.
P_{up-l}	Total active power load upstream to section l.
P_{down-l}	Total active power load downstream to section l.
$P_{fr,ij}$	The active power of line ij on the feeder fr.
$Q_{fr,ij}$	The reactive power of line ij on the feeder fr.
$P_{fr,jk}$	The active power of line jk on the feeder fr.
$Q_{fr,jk}$	The reactive power of line jk on the feeder fr.
λ_l	The failure rate of the section l.
$L_{\max}$	Length of the longest section on the feeder fr.
$SAIDI$	System average interruption duration index.
$ASAI$	Average service availability index.

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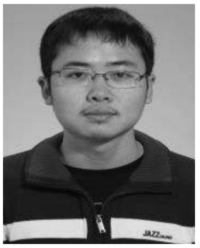

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