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Reliability Correlated Optimal Planning of Distribution Network with Distributed Generations

Yue XIANG[a], Yang WANG[a], Yunche SU[b], Wei SUN[c], Yuan HUANG[a*], Junyong LIU[a]

[a] College of Electrical Engineering, Sichuan University, Chengdu 610065, China
[b] State Grid Sichuan Economic Research Institute, Chengdu 610041, China
[c] School of Engineering, University of Edinburgh, Edinburgh, U.K

Abstract Integration of distributed generation (DG) in distribution network changes the topological structure of distribution network. Meanwhile, the location and size of DG as well as the evolution of the topology structure of distribution network will affect the power supply reliability, which will make the planning process of the distribution network extremely complicated. For this, this paper presents a new distribution network planning model with reliability estimation method. The several network templates are obtained with the hierarchical clustering algorithm based on tree edit distance (TED), which could reduce the complexity of the distribution network. Then, the topology characteristics of the clustered network templates will be correlated with reliability index, which is formulated as explicit formulation. Similarly, the correlation model between the reliability index and DG planning is established through BP neural network. Furthermore, the distribution network planning model under each network template is aggregated, which contains the established reliability estimation model. Investment costs of distribution networks with different network templates are analyzed for different scenarios. The results suggest that unlike existing solution techniques for reliability correlated distribution network planning, the proposed method can effectively converge to the optimal solution, and evaluate the investment performance for large-scale distribution networks.

Keywords Distribution network; optimal planning; distributed generation; tree edit distance (TED); reliability

1 Introduction

Under the background of the rapid growth of power demand and the shortage of fossil energy, the penetration of DG in the distribution network continues to increase due to its flexible operation strategy, environmental friendliness, etc [1,2]. However, the access of DG adds new power sources to the distribution network, which evolves the network topology and greatly affects the reliability and security of the distribution network [3]. It can be seen that the network topology of distribution network must be optimized and planned to adapt to the trend of interconnection for

*Corresponding author
E-mail address: yuanhuang@scu.edu.cn (Yuan HUANG)

large-scale renewable power generation. Therefore, on the premise of guaranteeing the economy and reliability of distribution network, how to get the distribution network planning scheme that is more conducive to the access of DG becomes the main problem that needs to be solved urgently in distribution network planning [4].

At present, a lot of work has been done on DG and network planning in distribution network [5-7], but the coupling between the two has not been considered in the planning model. With the increasing permeability of DG, it is necessary to consider the location and size of DG together with the network optimization to fully guarantee the reliability, economy, flexibility and safety of the system [8]. In addition, through the coordinated planning of DG and network, the system reliability cost can be reduced to maximize the investment benefit. However, when considering the large-scale dynamic combination optimization problem of power flow variation under the operation characteristics of system, the uncertainty of DG operation and network reconstruction, the AC constraints optimal power flow problems in the analytical model will become extremely complex in [9]. Therefore, the correlation rules of decision variables and distribution network reliability are established to replace the nonlinear and no-convex constraints of power flow and network security in the planning model, so as to realize the optimization of investment path rapidly in [10]. However, when 0-1 variables in network optimization are used as input items of the correlation model, the accuracy of the correlation model is reduced.

The distribution network planning mainly focuse on the reliability of the system [11,12]. At present, the analytical method and simulation method are the main algorithms for reliability evaluation. Simulation method takes advantage of monte carlo sampling to simulate the operating state of the system, to obtain statistical reliability index [13,14]. The analytical method specifically analyzes the influence range of each power failure, and accurately calculates the reliability index [15]. However, both of the above algorithms involve analysis and search of the network topology, but the network topology (including segmented switches, etc.) belongs to the variables to be optimized, which is unknown in the planning model. In other words, the analytical method and simulation method increase the complexity and non-linearity of the distribution network planning. An explicit formula was deduced for evaluating the reliability index of large-scale distribution network based on the actual structural characteristics of specific distribution network, which avoid the detailed analysis after failure in [16]. However, it is not strictly continuous differentiable due to the existence of judgment statements, and the algorithm has a relatively large error due to too many assumptions on feeders. Further, an improved explicit estimation algorithm for the reliability index with the typical network templates was proposed, which continued the calculation idea of explicit expression of the estimation algorithm [17]. Meanwhile, the reliability was included into the cooperative planning model of DG and network, but the model was only for simple radial topological network in [18,19]. It is difficult to calculate power flow when facing the large-scale and complex distribution network.

The above literature survey shows that the joint expansion planning of DG and distribution network, which cannot comprehensively consider the coupling effect of DG and distribution network, that is, the benefit evaluation brought by the collaborative planning model. In addition, the existing reliability evaluation methods are greatly influenced by the network topology. And network topology itself as the result of model optimization, which increases the complexity and nonlinearity for distribution network planning. Meanwhile, the simple radial topology is mainly studied in the distribution network planning which correlated reliability. For distribution network with large scale and complex structure, the solution strategy proposed in the above literatures cannot be effectively verified and implemented. In this regard, this papers proposes a distribution network planning model with reliability estimation method. In order to facilitate distribution network planning, this study is carried out on the topology templates after feeder clustering. The topology is represented as an adjacency matrix, and the network templates gained by the hierarchical clustering algorithm based on TED. For each network template, the network characteristics of the clustered network templates will be correlated with reliability index, which is formulated as explicit formulation. Similarly, the correlation model between the reliability index and DG planning is established through BP neural network. Therefore, the sub-planning model under each network template can be established and finally aggregated into the overall distribution network planning model. The proposed method is applied to the actual system, and then analyzed according to different investment scenarios. Finally, it is compared with the planning model based on the reliability evaluation of analytical method to verify the effectiveness of proposed method. The main contributions of this paper can be outlined as follows:

- A novel approach for clustering the network templates that classify the complex grid topology of the actual distribution network into limited and manageable network templates is proposed. This approach can reduce the difficulty of large-scale distribution network planning.
- A novel reliability estimation model is proposed to build a “fast track” between planning variables and reliability. The proposed model reduces the calculation errors caused by the differences in network structure,

and is suitable for embedding in the distribution network planning model.

- A discussion of the results for the coordinated planning of DG and network on different network templates and aggregation grid is posed, which provided new ideas for planners to make accurate investment strategies.

The rest of the paper is organized as follows. The network templates of the distribution network are obtained in section 2. In Section 3, the reliability estimation model of DG and network is established. Section 4 presents a cooperative planning model for the distribution network with DG, which includes the reliability estimation model in section 3. The example section is shown in section 5. Finally, conclusions are achieved in Section 6.

2 Network templates

2.1 Abstract representation of topology

Distribution network is a complex structure composed of lines, equipment and load, which is essentially a small-world network [20]. In order to extract the key information of distribution network and express it in the form of graph structure, it needs to be abstracted. An undirected graph structure composed of buses and edges is adopted to describe a complex distribution network [21]. The concrete abstraction process is shown in Fig. 1.

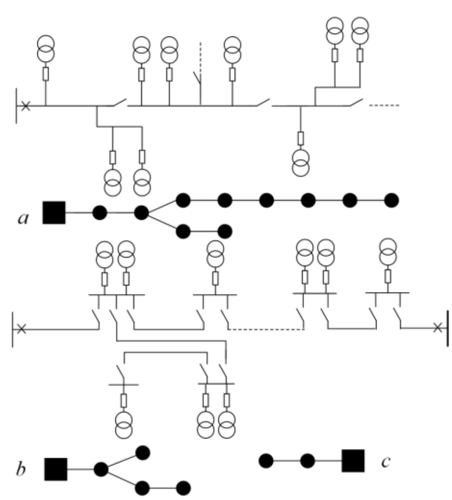

Fig. 1. Graph theory representation of distribution network structure

2.2 Tree Edit Distance (TED)

Before clustering the distribution network, it is necessary to introduce TED to calculate the similarity among different tree structures. Different TED will be used as the evaluation criteria for the subsequent clustering templates. First, Edit Distance [22] is defined as: for two strings $d(S, K)$, Edit Distance is described as the minimum number of times to make S and K become the same string by the following editing operations.

1) Replace S_i with K_j

2) Delete S_i or K_j

3) Insert characters in S_i or K_j

where S_i and K_j represent characters in S and K, the TED can be obtained from the edit distance [23]. The minimum cost required to convert one tree structure to another through steps 1-3 above. Then the TED between the two tree structures can be obtained by the following formula.

$$D(G_1, G_2) = \min \sum_{i=1}^{N} C(s_i) \tag{1}$$

where $S=\{s_1,s_2,\ldots,s_k\}$ represents the set of all editing operations that converted from tree structure G_1 to G_2, while N is the total number of operations, and $C(s_i)$ is the cost of tree editing operations of the s_i step.

Aiming at solving TED with multi-node tree structure topology, this paper adopts a recursive algorithm based on dynamic programming to improve the solving efficiency and computational accuracy for TED in distribution network [24]. In this algorithm, the two different tree structures are decomposed into multiple subtrees, and the edit distance between each subtree structure is calculated from the bottom of the tree to the top until the edit distance between all subtree structures is obtained.

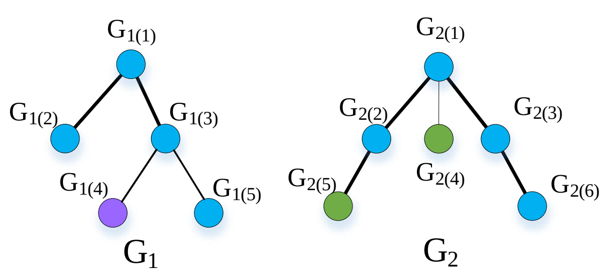

Fig. 2. Example of tree topology

Corresponding to the node numbers given in the Fig.2, isomorphic set $\boldsymbol{S}(G_1,G_2)$ can be defined. $\boldsymbol{S}$ is an array pair (i, j) composed of node numbers in G_1 and G_2. In Fig.1, the nodes of different color represent nodes that need to be deleted, inserted, and changed, while nodes of same color represent an isomorphic set of two trees. Therefore, the whole tree editing process is called mapping, so that the minimum cost required to convert from G_1 to G_2 can be solved in Eq. (2), namely.

$$D(G_1,G_2)=\min\Big(\sum_{(i,j)\in T}C_c(i,j)+\sum_{i\notin T}C_d(i)+\sum_{j\notin T}C_i(j)\Big) \tag{2}$$

In (2), C_c, C_d and C_i respectively represent the cost of replace, delete, and insert in node operation. During the transition from G_1 to G_2, insert related nodes not included in T_2, delete related nodes not included in G_1, and replace two subtree structures.

When the TED among specific subtree structures is calculated, it can be assumed that *r*(*i*) is the right-most node in the downstream node of node *i*, and then the subtree structure with *i* as the root node is constituted by nodes *i* to r(*i*). The TED between the two subtree structures composed of node r(i_1) to node *i* and node r(j_1) to node *j* is expressed as D(*G*), and then the dynamic programming equation of state can be obtained as shown in Eq. (3).

$$D(G^{r(i_1),i},G^{r(j_1),j})=\min\begin{cases}D(G^{r(i_1),i+1},G^{r(j_1),j})+C_d(i)\\D(G^{r(i_1),i},G^{r(j_1),j+1})+C_i(j)\\D(G^{r(i_1),r(i)+1},G^{r(j_1),r(j)+1})+\\\qquad D(G^{r(i),i+1},G^{r(j),j+1})+\mathrm{C}_c(i,j)\end{cases} \tag{3}$$

2.3 Hierarchical clustering based on TED

In the actual distribution network planning, there is no need to carry out specific analysis for each network topology, but only need to analyze the similar network structure. Meanwhile, further planning and research can be carried out on the similar network structure, thus reducing the overall complexity. Then, in the process of network clustering, it is required to represent the difference value between feeders through a matrix, and its definition form is as follows:

$$\begin{bmatrix}0 & & & \\ d(G_2,G_1) & 0 & & \\ d(G_3,G_1) & d(G_3,G_2) & \cdots & \\ d(G_n,G_1) & d(G_n,G_2) & d(G,G) & 0\end{bmatrix} \tag{4}$$

where d (G_i, G_j) in Eq. (4) represents the tree editing distance between G_i and G_j. When G_i and G_j are more similar, the value is closer to 0.

In this paper, the agglomerative hierarchical clustering algorithm based on TED is adopted to cluster the typical network templates *K*. Firstly, the TED between two of *N* feeders is calculated, then the two nearest feeders are merged to form *N*-1 classes. Then the distance between the merged new class and other classes is calculated, and the above process is repeated until all feeders are merged into one class or the termination condition is met. In the clustering process, TED is used as the distance between feeder, and the distance between the feeder is calculated by average distance.

$$L(C_i, C_j) = \frac{1}{n_i n_j} \sum \sum \left| G_i - G_j \right| \tag{5}$$

where C_i and C_j are two different categories; T_i and T_j are random samples in C_i and C_j; i, j=1,2,…,N; n_i and n_j are the total number of C_i and C_j, respectively.

2.4 Generation of the network templates

In Section 2.2, all network topologies are clustered so that clusters of different network topologies can be generated. However, even in the same clusters of distribution network, there are different system characteristics, such as the load capacity of different nodes, load density, line length, etc., these as the inherent attributes of different network topologies, also affect the reliability of the system. In order to define an optimal network templates from a network cluster, it is necessary to set the intrinsic attribute values of each network topology to a characteristic value that is most suitable for this kind of cluster. However, in practice, for a specific network cluster, each inherent attribute has a specified range, so the inherent attribute of different network topology under each cluster as the average value.

$$n_i = \frac{1}{K} \sum_{j=1}^{K} c_{r,j} \tag{6}$$

where n_i is the network template i; K is the number of network topologies in the network template i; $C_{r,j}$ is the inherent attribute r of network j.

3 Establishment of reliability estimation model

3.1 Explicit expression of network optimization and reliability

3.1.1 Analysis of Reliability evaluation

At present, the reliability of the system is mainly evaluated by the average outage time of the system (SAIDI) and average outage frequency of the system (SAIFI) [25].

$$S_D = \sum_{j=1}^{N_R} d_j N_{k,j} T_{k,j} / \sum_{i=1}^{N_F} N_i \tag{7}$$

$$S_F = \sum_{j=1}^{N_R} d_j N_{k,j} h_{k,j} / \sum_{i=1}^{N_F} N_i \tag{8}$$

where S_D, S_F are SAIDI and SAIFI respectively; d_j represents the failure rate of the device i in the line; N_R, N_F are the total number of devices and nodes in the feeder, respectively; $N_{k,j}$ refers to the number of users of category k after the failure of device j; $T_{k,j}$ is the corresponding power outage time; $h_{k,j}$ represents 0-1 variables of power failure state. The core idea of reliability evaluation is to directly analyze $N_{k,j}$ under certain assumptions. In the case of the same equipment failure, such as transformer and line failure, d_j is unchanged and $T_{k,j}$ are equal. Therefore, j in $T_{k,j}$ can be ignored, and Eq. (7-8) can be converted into:

$$S_{Fn} = N_{Rn} d_n (\rho_{an} h_a + \rho_{bn} h_b + \rho_{cn} h_c) \tag{9}$$

$$S_{Dn} = N_{Rn} d_n (\rho_{an} T_a + \rho_{bn} T_b + \rho_{cn} T_c) \tag{10}$$

$$\rho_{kn} = \sum_{j=1}^{N_R} N_{nj} / \sum_{i=1}^{N_F} N_i N_R \tag{11}$$

$$S_F = \sum_{n=1}^{Z} S_{Fn} \tag{12}$$

$$S_D = \sum_{n=1}^{Z} S_{Dn} \tag{13}$$

where N_{Rn} is the total number of equipment under class n equipment; d_n represents the failure rate/maintenance rate of a single equipment under class n equipment; If the lines fail, N_R is the total length of the lines; S_{Fn} and S_{Dn} respectively represent SAIFI and SAIDI of class n equipment; and Z is the total number of device classes.

The ρ_{kn} (k=a, b, c) in Eq. (12-13) means the user with ρ_{kn} ratio in feeder is called the class k user when the device of class n fails. In short, ρ represents the ability of load transfer and fault isolation in specific distribution network, which is greatly affected by the network topology. It also shows that ρ is the core of the explicit expression of network optimization.

3.1.2 Deriving the expression for ρ

Since parameter ρ largely determines the fault isolation of feeders. That is, the larger ρ is, the more users will be isolated after failure, and the stronger the fault isolation ability of feeders. Taking the analysis of actual overhead lines as an example. If the failure of any equipment in the feeder, the increase of section switches make the whole feeder only exists class a and c loads, and $\rho_a+\rho_c=1$. Furthermore, according to the equipment fault type, S_{Fn} and S_{Dn} can be respectively calculated by the analytic method, the ρ_{an} and ρ_{cn} are inversely deduced by (9-11). The ρ_{an} is the result of different feeder segment numbers P_F, so $\rho_{an}=f(P_F)$ can be fitted to the function expression of different feed segment number. Generally speaking, the fault isolation and transfer capacity of the system increase with the increase of the number of sectional switches in the feeder, and the reliability of the system also increases. Considering the characteristics of function, the variation trend of $\rho_{an}=f\,(P_F)$ can be approximated by the Fig. 3. The function used in each reference network topology is determined by the function form with the best regression effect and its parameters.

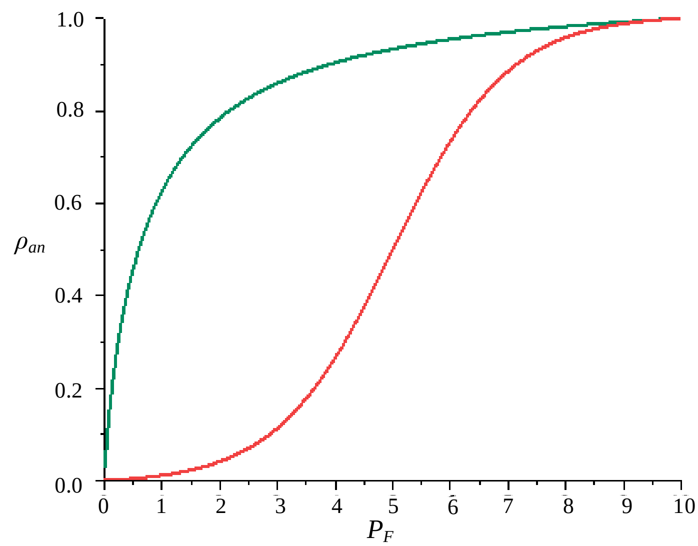

Fig. 3. Approximate form of $f\,(P_F)$ in regression function

In addition, it is assumed that after the failure occurs, there is a tie-line at the end of each feeder. Therefore, the end of the feeder can be regarded as the power supply point, and ρ_{cn} is continued to decompose into ρ_{bn} and ρ_{cn}. Thus, the function relation between ρ_{cn} and P_F, the transposing rate P_Z of the backup power supply can be further obtained, which expressed as follows:

$$\rho_{cn} = f\,(P_F, P_Z) \tag{14}$$

In order to reduce the complexity of function relation in regression fitting, the function expression of ρ_{an} =f(P_F, P_Z) is calculated respectively considering the absence of reserve capacity of feeder (P_Z=0%) and the reserve capacity of full feeder (P_Z=100%). By substituting Eq. (12-13) into Eq. (9-10), the functional relationship between reliability index and P_F, P_Z can be established, which can be embedded into the planning model.

3.2 Correlation model of DG and reliability

3.2.1 Correlation analysis of DG and reliability

In the actual distribution network planning, the DG installation node is related to the reliability of the system. In Fig. 4, when all nodes in IEEE 33 install DG with the same capacity, installing DG in bus 10-22 can greatly improve the reliability of the whole system. In addition, if do not consider the uncertainty of DG output, the same bus installed with different capacity of DG will also affect the reliability of the system.

In the DG planning model with reliability, the embedded reliability calculation program is often used to obtain the corresponding reliability index value according to the alternative scheme. Therefore, the DG planning model based on optimal power flow and network constraints is nonlinear, which solved by heuristic algorithm could increase the computational costs and risks. In this paper, BP neural network is considered to establish the correlation model between DG and reliability. By replacing the nonlinear and nonconvex part of the traditional programming model with the established correlation model, the complex problems in the optimization process can be solved effectively.

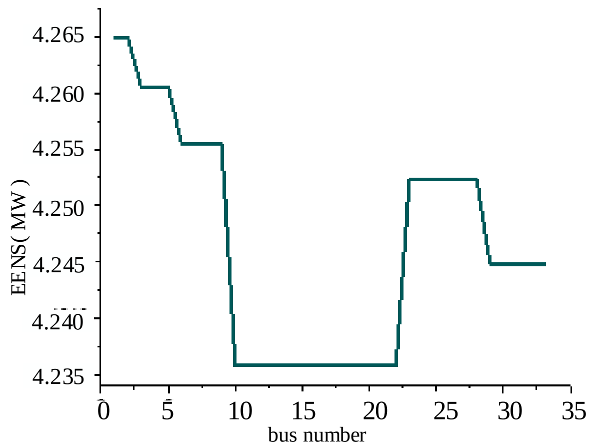

Fig. 4. Diagram of reliability index and installation location of DG in IEEE 33

3.2.2 Correlation model on BP neural network

Considering the complex coupling of DG and reliability, this paper adopts BP neural network to explore the correlation model between them [26]. In addition, neural network can well fit data containing nonlinear correlation relations, so it has certain advantages for the establishment of high-dimensional nonlinear complex correlation model.

BP neural network is mainly composed of input layer, hidden layer and output layer, and BP model is a multi-layer network model trained in accordance with the error back-propagation mechanism. The adjacent layers are connected with each other, and the training samples are transferred from the input layer to the hidden layer to activate neurons until the output layer. The weight value of neurons is adjusted by the gradient descent strategy, so that the error value between the target output and the actual output becomes smaller, which could ensure the continuous improvement of model accuracy.

For the BP neural network with N hidden layers, the calculation formula of each training sample is as follows:

$$z^{(k+1)}(i)=\sum_{j=1}^{S^{(k)}}\omega^{(k+1)}(i,j)x^{(k)}(j)+b^{(k+1)}(i) \tag{15}$$

$$y^{(k+1)}(j)=h^{(k+1)}(z^{(k+1)}(i)) \tag{16}$$

$$x^{(0)}(j)=I(j),\quad \forall j\in\{1,\cdots,S^{(0)}\} \tag{17}$$

where k=0, 1, ... , N; $\omega^{(k)}(i, j)$ is the weight value of neuron i in the k layer to the neuron j in the k+1 layer; and $S^{(k)}$ is the number of neurons in the k layer; $b^{(k)}(i)$ represents the bias value of the neuron i in layer k; $h(k)$ represents the activation function of neurons at layer k; $x^{(k)}(j)$ is the output value of the neuron j in layer k. The activation functions of BP neurons are mainly in the following forms:

Table 1 Activation function expression of BP network

name	Logsig	Purelin	Tanh
function	1/(1+exp(-x))	2/(1+exp(-2x))-1	x

Taking the sample data of new add load, DG installation capacity and installation location of the system as input of the neural network, and the reliability index as output, the whole expression can be written as follows:

$$\Phi_i(y^{(k+1)},x^{(k)},\omega^{(k+1)},b^{(k+1)})=0 \tag{18}$$

An correlation model between DG and reliability is obtained through the training of BP neural network, which can be embedded into the subsequent planning model.

3.3 Joint reliability model between DG and network

Since the DG can be adopted as a backup power supply in the distribution network, the location and size of the DG will inevitably affect the planning results of network. From another perspective, the fitting results between network and reliability are affected by the correlation model of DG and reliability. Therefore, the corresponding joint reliability model can be obtained according to the network and DG:

$$F(P_F, f(DG))=0 \tag{19}$$

where, f (DG) is the correlation model of DG and reliability, and P_F is the sectionalizing switch related to network planning.

4 Planning model based on reliability estimation method

For the traditional collaborative planning model of network and DG, investors tend to minimize the total cost, including flow constraint and system security constraint. The traditional planning model is used to judge whether the decision variables meet the constraint conditions by continuously calculating the power flow under different section t within the planning year Y. And guide the final planning scheme to meet the comprehensive cost of the whole planning model. However, each power flow calculation increases the total time, and the power flow may not converge in the calculation process, which would lead to errors in the optimization results. Moreover, for the more complex and high-dimensional networks, the solution process becomes extremely difficult.

4.1 Proposed planning model

In view of the deficiencies and defects in traditional planning model, Eq (19) in Section 3.3 is substituted for the power flow and system security constraints in traditional planning model, so as to establish the coordination planning model of distribution network and DG. It can satisfy the reliability constraint of the programming and accelerate the solving speed of the model. In addition, complex power flow calculation and reliability iterative calculation in traditional model are avoided. By building planning models on different network templates, the models are aggregated into practical planning models for distribution network with large-scale and complex structures.

In this paper, planning decision-making problems are divided into two categories from the aspects of planning to improve economy and distribution network performance: minimum comprehensive investment cost under reliability constraint conditions; maximize reliability performance under investment amount constraints.

4.1.1 Minimum comprehensive investment cost under reliability constraint conditions

Aiming at the planning of distribution network and DG under complex topologies, an optimal reliability level is designed to minimize the total social cost. Therefore, planning is carried out for each network template and finally aggregated into one planning goal:

$$\begin{cases} \min\limits_{x,y} F = \sum\limits_{i=1}^{N}[k_i S_i (C_{invest}^i + C_{EENS}^i)] / \sum\limits_{i=1}^{N} k_i S_i \\ g(x,y) = 0 \\ h(x,y) \le 0 \end{cases} \tag{20}$$

where x represents the variables related to network structure; y represents the variables related to location and size of DG; C_{invest}^i is the investment cost of DG and network under the network template i; C_{EENS}^i is the outage loss cost under the network template$i$; N represents the number of network templates; k_i is the total number of topologies in the network template i; S_i is the total load under the network template i; $g(x, y)$ is the equality constraint of the investment planning model, namely the reliability index; $h(x, y)$ is the inequality constraint, including the upper limit of the number of DG installations and the upper limit of section switches under each network template. The subobjective functions C_{invest} and C_{EENS} are calculated as follows:

$$C_{invest}^i = r_x c_x^{In} + r_y c_y^{In} + c_x^{Op} + c_y^{Op} \tag{21}$$

$$C_{EENS}^{i}=\sum_{i=1}^{N_{br}}\sum_{j=1}^{N_l}\lambda_i r_i \frac{Dur_j}{Y} f_{i,j}^{t} \tag{22}$$

where r_x, r_y are the investment recovery rates of network and DG respectively; c_x^{In}, c_y^{In} are the initial investment cost of network and DG; c_x^{Op}, c_y^{Op} are respectively the operation and maintenance cost of network and DG; N_{br} is the number of network topology branches; N_l is the number of load levels; λ_i、r_i are the failure rate and repair time for circuit i, respectively; Dur_j represents the duration of load grade j; $f_{i,j}^{t}$ is the tidal current through line i.

Each network template is evaluated separately and aggregated for a regional complicate topology. Therefore, the reliability index of the aggregated distribution network can be calculated as the following equations:

$$\begin{cases} FI=\sum_{i=1}^{N} k_i S_i FI_i / \sum_{i=1}^{N} k_i S_i \\ DI=\sum_{i=1}^{N} k_i S_i DI_i / \sum_{i=1}^{N} k_i S_i \\ FI_i = FI_i(P_F, DG) \\ DI_i = DI_i(P_F, DG) \end{cases} \tag{23}$$

where *FI*, *DI* respectively represent the reliability index SAIFI and SAIDI under the regional aggregated feeders; *N*, k_i and S_i in Eq (23) have the same meaning as those in Eq (20). FI_i, DI_i respectively represent SAIFI and SAIDI model of aggergation in Section 3.3 under the network template *i*; Therefore, Eq (23) is the equality constraint in Eq (20).

4.1.2 Maximize reliability performance under investment amount constraints

If the reliability of distribution network is taken as the objective function and the total investment amount is taken as the constraint condition, the corresponding model is as follows:

$$\min(FI, DI) \tag{24}$$

$$\sum_{i=1}^{N}[k_i S_i (C_{invest}^{i} + C_{EENS}^{i})] / \sum_{i=1}^{N} k_i S_i \le C_{\max} \tag{35}$$

In addition, the equation constraint should satisfy the upper limit of installed capacity of DG and upper limit of network. In this way, the maximization of distribution network performance can be achieved with limited capital.

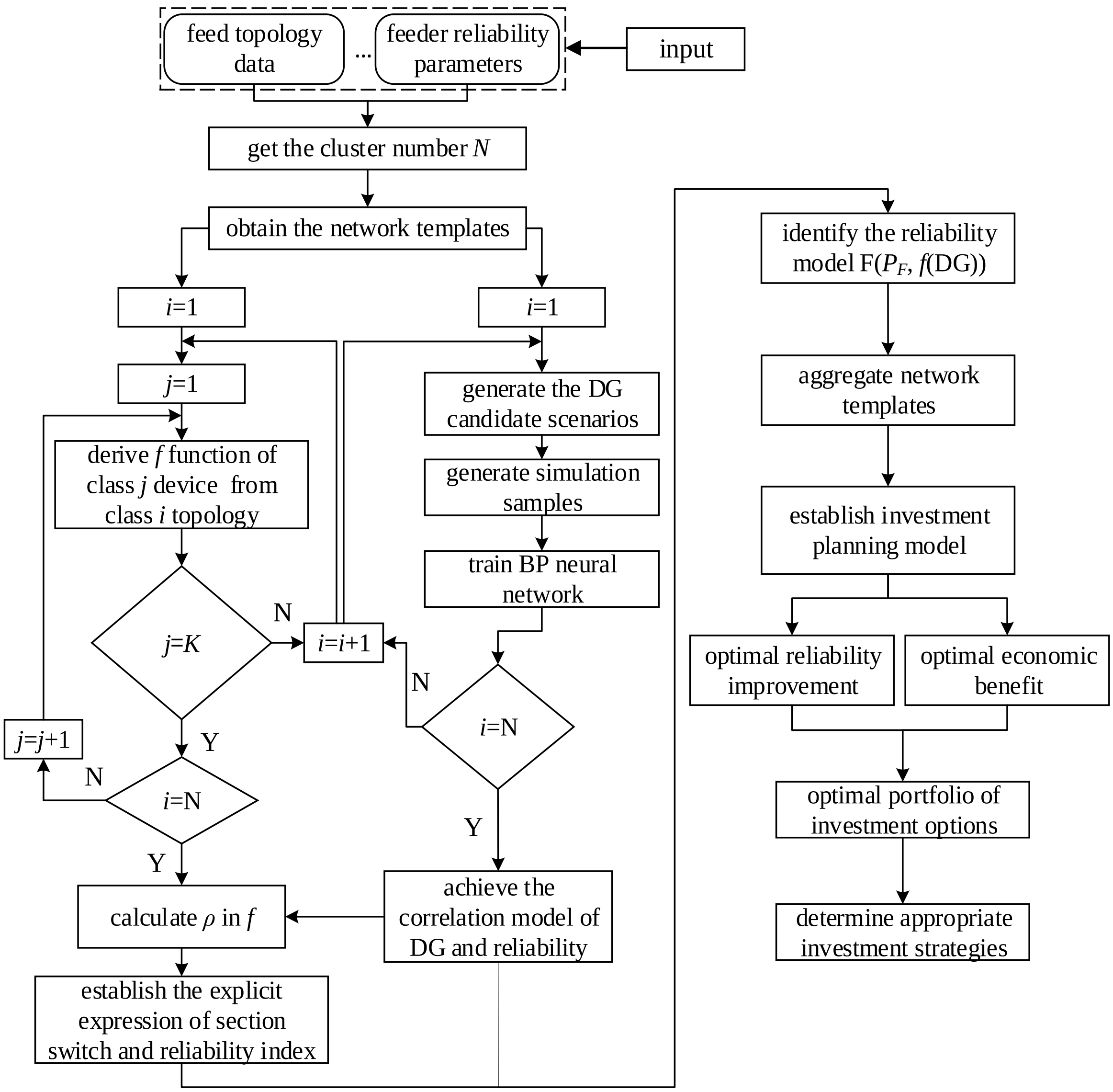

Fig. 5. Flowchart of the proposed method for reliability correlated distribution network planning with DG

4.2 Flowchart for the proposed model

Traditional planning model of DG and network are generally based on intelligent algorithms or linearization of nonlinear constraints by numerical methods to obtain the optimal investment planning scheme. The planning model proposed in this paper is collaborative planning of network optimization and DG planning oriented to regional complex topologies. Through explicit expression and correlation model based on reliability, the optimal programming results can be obtained directly. Based on the above analysis, the calculation process of the overall planning model is shown in the Fig. 5.

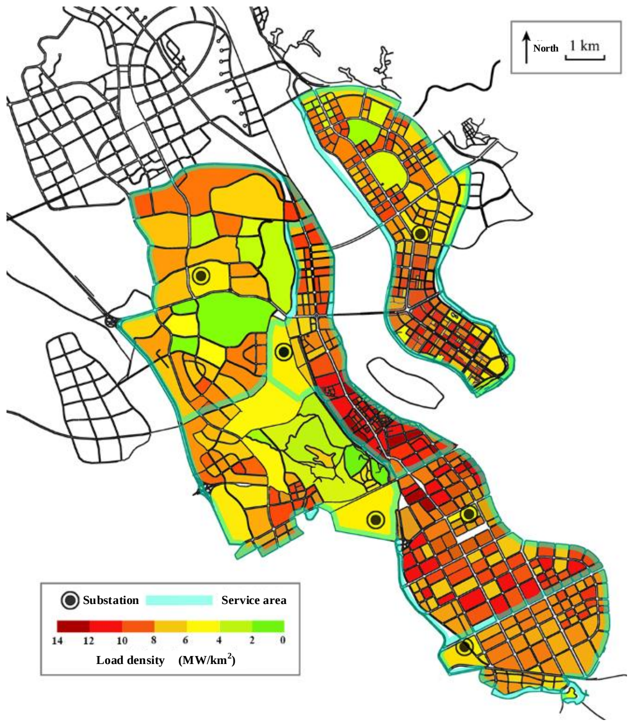

Fig. 6. Actual distribution network power supply range and load density distribution

5 Case Study

5.1 Case description

This paper selects the distribution network of a city for the collaborative planning of network and DG to verify the feasibility and effectiveness of the proposed method [27]. The real distribution network shows the load density distribution in Fig. 6. In addition, there are 6 x 110kV and 4 x 35kV substations respectively, 96 x 10 kV feeders and 2047 distribution transformers. Among them, the failure rate of overhead lines is 0.065 times per year, the failure rate of cable lines is 0.043 times per year, the repair time is 5h, and the power failure time of feeder users are 1h, 1.5h and 6h respectively.

Firstly, all 10kV feeders in the distribution network are clustered, among which C_d, C_i and C_c are set to 1 and 0 in TED parameter. The optimal cluster numbers 4 can be obtained through the TED based hierarchical clustering method, and the proportion of various feeders can be shown in Table 2. Furthermore, according to the parameters of different networks in each template, the most suitable load data and line impedance value of typical network nodes can be obtained, so as to obtain the network templates. Therefore, the network templates are further used as the benchmark networks for planning.

The DG candidate installation nodes for network template 1 are 4,10,14,24; The DG candidate installation nodes of network 2 are 10, 17, and 24; The DG candidate installation nodes for network template 3 are 6,11,16,24; The DG candidate installation node for network template 4 is 7,11. And the maximum allowable installation capacity of each node of the four network templates are 0.4MV, 0.2MV, 0.5MV and 0.3MV respectively. The maximum installation quantity of section switches of each reference topology is 6. In addition, system SAIDI is taken as the reliability index.

Table 2 Proportion of reference network topology

Type	1	2	3	4
Proportion (%)	0.14	0.24	0.2	0.42

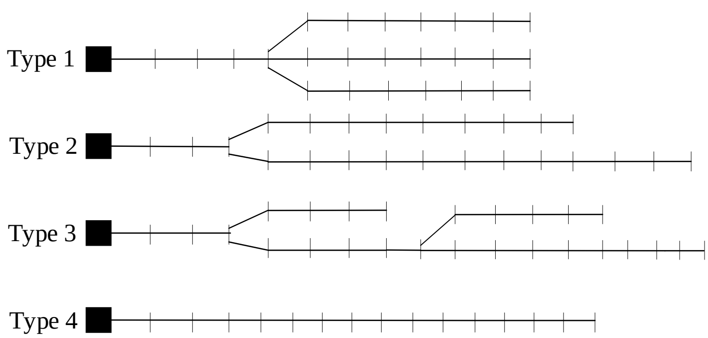

Fig. 7. Structural diagram of network templates

5.2 Simulation results

5.2.1 Analysis of planning results under the different scenarios

In order to verify the effectiveness of the proposed model in this paper, the planning results under different planning scenarios and the performance improvement of the whole service area are considered and analyzed. The lines are divided into overhead lines and cable lines, and two planning schemes are considered under the scenario of 0% and 100% transfer rate: 1. only planning DG, not considering sectionalizing switch; 2. coordinated planning of DG and sectionalizing switch. Taking economic construction as the target, two schemes are calculated respectively, and their planning results are shown in Table 3-6.

Table 3 Overhead line (Pz=0%) under scenario 1

Scheme	Topology type	DG location(capacity/MW)	Number of sectionalizing switches	Cost(CNY)
1	type 1	4(0.03),10(0.02),14(0.02)	-	293.4e4
	type 2	10(0.03),24(0.035)	-	
	type 3	11(0.4),16(0.03),24(0.02)	-	
	type 4	11(0.45)	-	
2	type 1	10(0.02),14(0.03),24(0.01)	4	256.55e4
	type 2	17(0.03),24(0.03)	5	
	type 3	11(0.4),16(0.02),24(0.02)	3	
	type 4	11(0.4)	2	

Table 4 Overhead line (Pz=100%) under scenario 2

Scheme	Topology type	DG location(capacity/MW)	Number of sectionalizing switches	Cost(CNY)
1	type 1	4(0.03),10(0.01),14(0.02)	-	259.43e4
	type 2	10(0.03),24(0.02)	-	
	type 3	6(0.36),16(0.03),24(0.04)	-	
	type 4	7(0.38)	-	
2	type 1	4(0.02),10(0.02),24(0.01)	4	249.60e4
	type 2	10(0.02),24(0.02)	4	
	type 3	6(0.3),11(0.04),24(0.02)	2	
	type 4	11(0.3)	2	

Table 5 Cable line (Pz=0%) under scenario 3

Scheme	Topology type	DG location(capacity/MW)	Number of sectionalizing switches	Cost(CNY)
1	type 1	4(0.02),10(0.02),14(0.02)	-	279.44e4
	type 2	10(0.028),17(0.03)	-	
	type 3	6(0.52),11(0.01),16(0.03)	-	
	type 4	7(0.32)	-	
2	type 1	4(0.02),10(0.02),14(0.02)	3	251.358e4
	type 2	10(0.03),17(0.03)	4	
	type 3	6(0.5),11(0.04),16(0.02)	2	
	type 4	7(0.3)	2	

Table 6 Cable line (Pz=100%) under scenario 4

Scheme	Topology type	DG location(capacity/MW)	Number of sectionalizing switches	Cost(CNY)
1	type 1	4(0.05),10(0.02),14(0.04)	-	251.67e4
	type 2	10(0.03),17(0.05)	-	
	type 3	6(0.05),11(0.28),16(0.04)	-	
	type 4	7(0.32)	-	
2	type 1	4(0.04),10(0.01),14(0.02)	2	247.419e4
	type 2	10(0.03),17(0.03)	3	
	type 3	6(0.06),11(0.2),16(0.02)	3	
	type 4	7(0.25)	2	

In Table 3-6, it can be seen from scheme 1 that the investment cost of DG decreases as the overhead line change to the cable line. The main reason is that the reliability of the cable line is higher, and the loss of the line is reduced, so the investment cost decreases in the face of the reliability constraint. In addition, the cost of investment is significantly reduced in the face of a radial network with transfer source. For scheme 2, it can be seen that the newly added load can be met by planning DG, and the correlation between DG and system reliability is greater than the influence of switch on system reliability, so the input of DG can greatly improve system reliability. However, since the unit investment cost of DG is relatively high, the overall investment cost of the system can be reduced after the rational planning of sectionalizing switches, and the reliability level constraint of the system can also be satisfied with the increase of the number of sectionalizing switches.

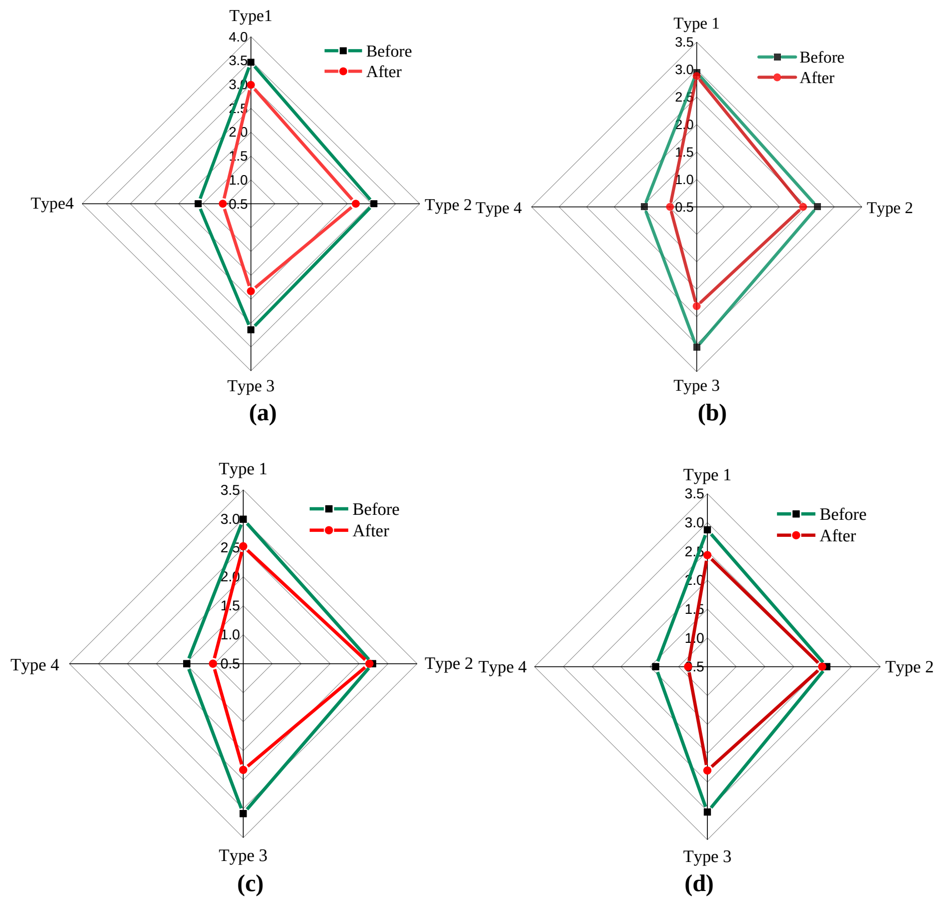

Fig. 8. Comparison of **EENS** before and after planning in different scenarios

When the transfer rate of overhead lines is 0%, there is no transfer of terminal backup power supply after line failure, so the investment cost of DG and sectionalizing switches must be increased to improve the low reliability level of the system. When the transfer rate of overhead lines is 100%, the backup power source is added to the end of the line, so the initial reliability of the network is relatively high. Therefore, the installed capacity of DG is less than that of scenario 1, and the number of sectionalizing switches are reduced. In scenario 3, the total investment cost is lower than those in scenario 1, because the failure rate of the cable is lower than that of overhead line and the line loss is reduced. Therefore, the supply shortage load of the system decreases slightly and the reliability level of the system is improved. However, the investment cost difference between scenario 2 and scenario 3 is small due to the existence of transfer power supply. In scenario 4, the reliability level of the system is already higher than that of scenario 1-3, so the reliability constraint can be satisfied through a small optimal configuration. Therefore, the final total planning cost is significantly less than the cost of scenario 1-3.

In order to further analyze the reliability improvement effects of different network templates under the optimal planning scheme of each scenario. Fig. 8 shows the system EENS values before and after planning under different scenarios. Because the total load of each template is different, the EENS before planning is different. However, it can be clearly found that in all scenarios, the EENS improvement effect of template 3 and template 4 is the most obvious, indicating the importance of considering reliability constraints in the planning of topology structures with fewer branches. However, templates 1 and 2 with a large number of branches have a higher degree of reliability, so they invest less in the reliability cost.

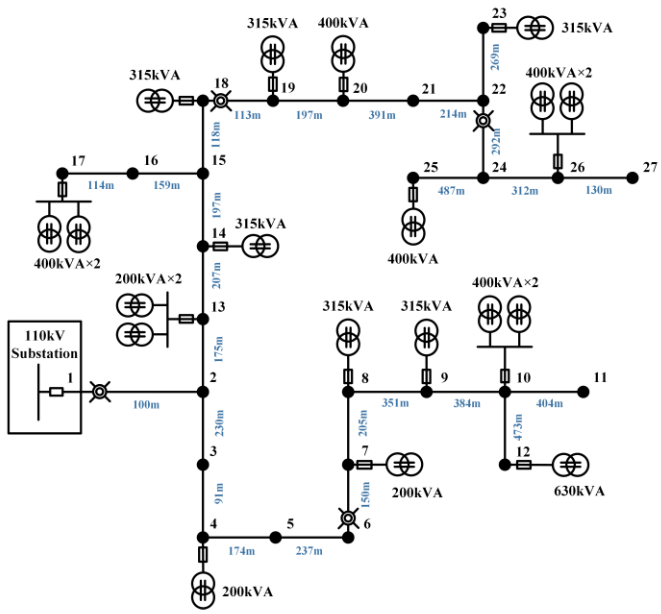

Fig.9. Feeder electrical wiring diagram

5.2.2 *Comparison and verification of the proposed reliability estimation method*

In addition, in order to further illustrate the feasibility of the proposed reliability estimation model, a radial feeder is selected from the actual feeder for the collaborative planning of DG and sectionalizing switch. The real radial feeder are shown in Fig. 9, and the topology of this type of feeder belongs to the second type of network template. The reliability estimation model proposed in this paper is compared with the traditional reliability planning method (analysis method). Under the same initial conditions of the two methods, the comparison of solution results is shown in Table 7, and the comparison of voltage changes of each bus is shown in Fig. 10.

Table 7 Comparison of results under different planning method

	EENS(MW)	Cost(CNY)	Time(s)
Initial system	6.3123	-	-
Traditional method	5.1434	137.2e4	132.4
Proposed method	4.9442	140.4e4	2.5

It can be seen from Table 7 that the optimization results of the traditional reliability construction is the target and based on the reliability estimation model proposed in this paper are respectively 18.52% and 21.67% for reducing the

EENS value of the system. However, the investment cost of the traditional planning method is 32,000 yuan more than the planning method proposed in this paper. From the perspective of reliability improvement and investment cost constraint, it shows the feasibility of the reliability estimation model proposed in this paper for cooperative planning of DG and network. In addition, from the time comparison of the optimization process, the proposed method can get the optimal feasible solution of the investment scheme more efficiently.

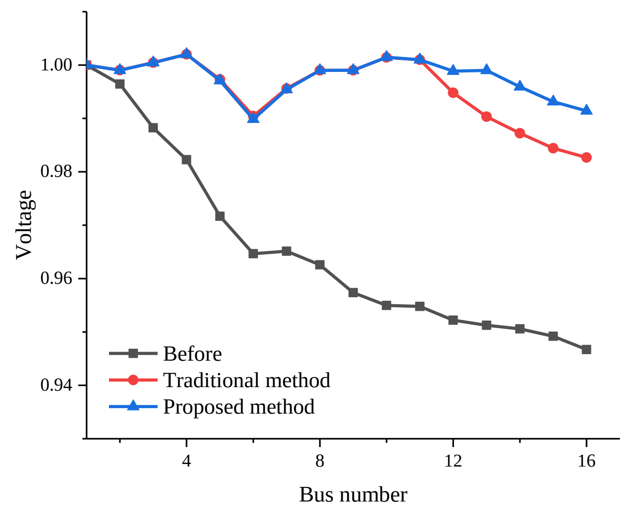

Fig. 10. Comparison of voltage value

In Fig. 11, the voltage amplitudes of the two planning methods for lifting nodes 1-11 are consistent. As the decision-making result of the method proposed in this paper has DG installation point at node 11, it gives full play to the regulation ability of feeder end voltage, making the range of node voltage fluctuation smaller. It shows that the proposed method can effectively solve the problem that the system voltage is low due to the new added load.

6 Conclusion

For the complexity of coordinated planning for DG and grid in distribution network, this paper proposes a novel planning method based on reliability estimation. The proposed method can effectively evaluate the investment performance of complex and large-scale distribution networks, including reliability and investment costs. The reliability estimation model can effectively adapt to different grid structures, and achieve a "fast track" between investment measures and reliability indexes. Simulation results presents the following

1) The reliability value of the network topologies in the same cluster fluctuates in a small interval, and the optimal investment cost is similar to a typical network template.

2) The coordinated planning of DG and network (sectional switch) can effectively improve the reliability of the system. In addition, under the requirement that reliability is met, the investment cost of DG and grid co-planning is

less than the cost of DG planning.

In addition, the overall performance (calculation time, investment cost, and reliability improvement) of the proposed method is significantly better than the planning method based on heuristic reliability evaluation. In future work, we will attempt to further improve the accuracy of the network clustering algorithm, and work to apply the proposed method to practical industrial applications.

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