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A Practical Large-Scale Distribution Network Planning Model Based on Elite Ant-Q

ZIYAO WANG, DAN LIN, GUANGXUAN ZENG, AND TAO YU, (Member, IEEE)
School of Electric Power, South China University of Technology, Guangzhou 510640, China
Guangdong Key Laboratory of Clean Energy Technology, South China University of Technology, Guangzhou 510641, China
Corresponding author: Tao Yu (taoyu1@scut.edu.cn)

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ABSTRACT In order to effectively apply the detailed geographic and load information provided by digital technology, this paper proposes a practical double-Q planning model for large-scale medium voltage distribution network. Meanwhile, a coding method and an elite Ant-Q algorithm(EAQ) suitable for solving the model in this paper are proposed. Based on the basic characteristics of the medium voltage distribution network, the components in the distribution network are abstracted into nodes and branches in the graph theory. A variety of practical issue, such as cost parameters (investments, maintenance, reliability) and technical constraints (feeder capacity constraints, number constraints of substation feeder), as well as road network constraints and connection mode constraints are taken into consideration. In addition, the storage of road network matrix information, reliability evaluation algorithm and model solving algorithm are suitable for large-scale distribution network. Finally, the proposed model and algorithm are applied to a business area to be planned in Guangzhou, which verifies the effectiveness of the proposed model and algorithm.

INDEX TERMS Large-scale distribution network planning, double-Q planning, EAQ, sequence coding, shortest path method, closed loop design.

NOMENCLATURE

INDICES

i_f, j_t	Index of road network branches, from bus i_f to bus j_t
i, j	Index of electrical node i, j
p	Index of load type(including residential, commercial, industry and institutional load)
s	Index of station node

SETS

$\boldsymbol{B}$	$m\times 3$ road network information matrix
Ω_L	Index set of all load nodes in the planning area
Ω_S	Index set of all substation nodes in the planning area
K	Index set of all feeders in the planning area
S	Index set of all station nodes in the planning area

PARAMETERS

$C_{\mathrm{I,t}}^{\mathrm{line}}$	Investment and construction cost per unit length of t-type lines, including overhead lines and cable lines
$C_{\mathrm{I,t}}^{\mathrm{equ}}$	Investment and construction cost of t-type switch equipment, including sectional switches and switch cabinets
r	Discount rate
τ	Planning years
$C_{\mathrm{M,t}}^{\mathrm{line}}$	Maintenance cost per unit length of class t-type line, including overhead lines and cable lines
$C_{\mathrm{M,t}}^{\mathrm{equ}}$	Maintenance cost of t-type switch equipment, including sectional switches and ring-network cabinets
U_K^e	Rated voltage of feeder K
η	Penalty coefficient
α	Learning factor
γ	Discount factor
W	Reward constant
M	Optimal number of agents
N_A	Number of Agents
N_C	Maximum number of iterations
δ	Importance of $\boldsymbol{AQ}$ matrix
β	Importance of $\boldsymbol{HE}$ matrix
q_0	Greed ratio

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q	Exploring weights
M_e	Number of elite agent
W	Reward constant

VARIABLES

n	The total number of nodes in the network
x_{ijk}	Whether feeder k is connected to load node i first and then to load node j
x_{ik}	Whether feeder k supplies power to load node i
B_{sk}	Whether feeder k is drawn from substation s
U_i	Outage time of load node i
m	Number of branch roads in road network
L_{ij}	Length of road network branch between node i_f and node j_t
d_{ij}	Shortest path length between electrical node i and j
n	Total number of nodes in the network
l	Total number of feeders
n_s	Number of power nodes
N_p	Number of constraints that are not satisfied
$M^s_{\max}$	Maximum number of feeder lines allowed to be drawn from substation s
p^s_0	Probability of the agent being assigned to substation s
M_s	Number of feeder lines that can be drawn from the current substation s
p^s_0	Probability of the agent being assigned to substation s
q	Random number between [0,1]
ε	Proportion of greedy strategies
HE	Heuristic matrix
$J_k(s)$	The next set of connectable load nodes when the current connection load node is s at the k th iteration
R	Feeder Connection Scheme
R_{gb}	Optimal Feeder Connection Scheme
F_h	Fitness function of agent h
F_{gb}	Fitness Function of Optimal Agent

ABBREVIATIONS

SCDF	Sector customer damage function
RN	Radial Network
SRN	Single Ring Network
TSOB	Two Supplies and One Backup
SPM	Shortest path method
DNP	Distribution network planning
EAQ	Elite Ant-Q algorithm
GWO	Grey wolf optimization
TLBO	Teaching-learning-based optimization
MVO	Multi-Verse Optimization
WOA	Whale Optimization Algorithm
AGC	Automatic generating control
GCD	Generation command dispatch

I. INTRODUCTION

Nowadays, with the development of digital platform [1], [2], distribution network modeling needs further integration of various system platforms on the basis of Common Information Model standard. Hence, it is a great challenge for planners to effectively utilize the abundant data information provided by digital modeling technology to carry out global intelligent planning for large-scale distribution network [3], [4].

So far, an enormous variety of studies have been undertaken for distribution network planning, in which the optimal distribution network components have been planned using different models and algorithms. For example, the optimal planning of distributed generations in [5], energy storage in [6], and RCS in [7], have been proposed. One of the planning contents is grid structure, which is carried out under the complex objective function considering technical, economic and topological constraints. However, most of these studies are only at the theoretical level and are rarely applied to engineering practice.

The essence of modern intelligent distribution network planning is to find the optimal scheme to provide sufficient and reliable power for a series of loads spatially distributed over a geographic zone, which has been demonstrated that it is a complex large-scale discrete non-convex problem [5]. In addition, it is of great significance to consider the connection mode and network constraints of distribution network to make distribution network planning more practical. Moreira *et al.* proposed a large-scale distribution network planning model, which can obtain the optimal distribution network under radial constraints with higher efficiency by using branch exchange method and parallel computing [6]. Boulaxis and Papadopoulos established a distribution network planning model considering GIS and applied dynamic programming to solve it [7]. Jabr obtained a disjunctive conic program for distribution network planning model, and reach the global optimal solution by using MILP [8].

The above models can obtain the global optimal solution by classical mathematical method. However, the solution time increases greatly when involving a large number of discrete variables. Due to the little dependence on models, heuristic algorithms are widely employed in distribution network planning [9]–[11]. In recent years, a few scholars have used explicit expressions to calculate the reliability of the specific distribution network, and used mathematical methods (such as MIP, MILP algorithms) to carry out distribution network planning research [12], [13].

Current research mainly takes investment cost and operation cost as objective functions, and N-1 security check or reliability check as constraints to optimize distribution network [14], [15]. Few studies take reliability as objective function in distribution network planning. At the same time, the existing distribution network planning model lacks consideration of the topology of distribution network and the influence of tie switches when carrying out reliability calculation. In order to meet users' requirements for high reliability, smart grid planning should take into account both economy and reliability. (that is, Double-Q planning, considering both Quantity and Quality [16]). Therefore, this paper attempted to establish a model and propose a novel algorithm for solving these problems.

The major contribution of the study can be summarized as follows:

1) A double-Q planning model of large-scale distribution network was established for the first time, which changes the rough way of global planning of distribution network, realizes the coordinated planning of economy and reliability, and achieves the goal of optimizing the comprehensive cost of distribution network planning.
2) The reliability evaluation algorithm was applied to the planning model, which is suitable for large-scale distribution network. The economic losses caused by different types of load blackouts are calculated by using the sector customer damage function (SCDF), which exactly quantifies the reliability of the planned distribution network.
3) The algorithm was well integrated with graph theory. On the one hand, the shortest path adjacency matrix is defined to store road network information and be used in distribution network planning model. On the other hand, the connection mode was abstracted and the tie line is set based on SPM, which overcomes the shortcoming of previous distribution network planning models that only consider radial constraint without connection mode constraint.

This paper is structured as follows: Section II provides the method of distribution network topology data processing and topology abstraction. Based on the topological abstraction of node and branch, Section III established a practical double-Q planning model for medium voltage distribution network, which includes the strategy of tie line setting. Subsequently, Section IV proposed the sequence coding method and EAQ for solving the model in this paper. Section V applies the model and algorithm to an unplanned district in China and analyzes the result. Finally, Section VI summarizes the paper and the future research direction is prospected.

II. TOPOLOGY ABSTRACTION OF DISTRIBUTION NETWORK PLANNING

A. NODE BRANCH ABSTRACTION

In Chinese urban medium voltage distribution network, the load of distribution transformer in overhead lines is connected to the overhead trunk lines through fuse, and the load of distribution transformer in cable network is connected to the feeder through ring-network cabinet. Therefore, the basic units of overhead lines and cables assumed in this paper are shown in FIGURE 1. The basic components of equipment considered in this paper are shown as follows: line l, circuit breaker b, sectional switch s, fuse f, distribution transformer u and load LD.

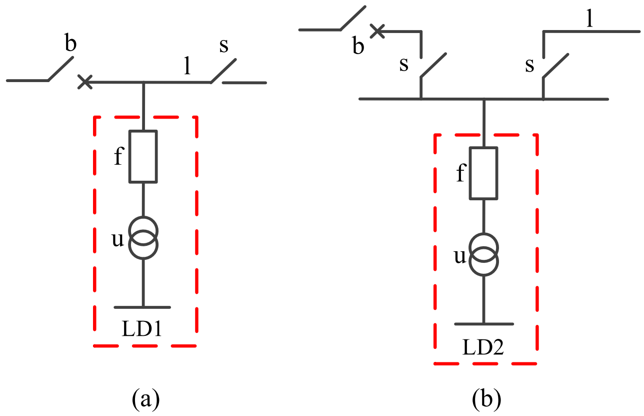

FIGURE 1. Schematic diagram of node - branch in feeder. (a) is overhead line. (b) is cable line.

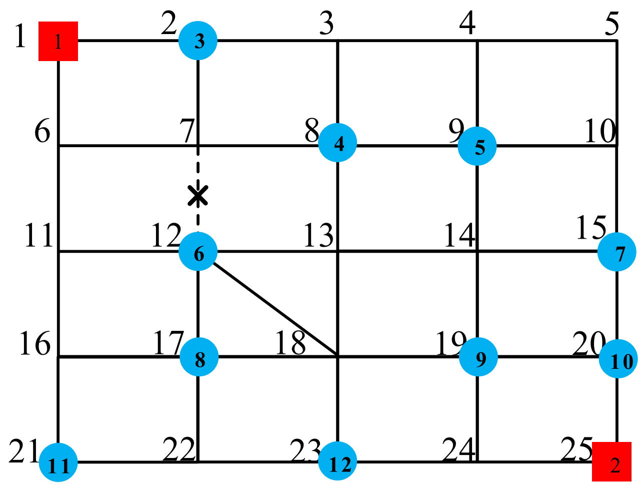

FIGURE 2. Diagram of network area.

In this paper, the components in the red dotted box are abstracted as nodes. The overhead line segment between two sectional switches is abstracted as branch, and the cable line between two ring-network cabinets is abstracted as branch.

B. DATA PROCESSING OF ROAD NETWORK TOPOLOGY

Before carry out distribution network planning, it is necessary to import relevant data and process them. The network information is contained in XML file from GIS, and the required topology information is obtained by parsing it.

Taking a simple functional area network as an example, the network is divided according to the road network as shown in FIGURE 2. The grid intersection of nodes 1-25 is the road network node, the solid line represents the connectable road, and the dotted line represents the unconnectable road. The red rectangles and blue circles in the figure represent the substation node and the load node respectively, which are referred to as electrical nodes in this paper.

For the purpose of storing data information of large-scale topology, the road network branch information matrix is defined as follows:

$$\boldsymbol{B} = \left[i_f, j_t, L_{ij}\right]_{m\times 3} \tag{1}$$

where, i_f and j_t represent the first node and the last node of the corresponding road network branch respectively. L_{ij} represents the length of road network branch between node i_f and node j_t. m is the number of road network branches. $\boldsymbol{B}$ can be regarded as sparse matrix.

There are some special cases in the network area that need special treatment:

1) If the line between two geographical nodes cannot be constructed, the branch length L_{ij} of it is set as infinite. Branch 7-12 in FIGURE 2 can be represented as [7, 12, ∞].
2) If there is an oblique line between two geographical nodes, it is directly added to the matrix. Branch 12-18 in FIGURE 2 can be represented as [12, 18, $L_{12,18}$].

C. SHORTEST PATH ADJACENCY MATRIX

After obtaining the road network information matrix, the shortest path between any two electrical nodes can be calculated by Dijkstra algorithm [17]. Meanwhile, the road network branch information matrix can be transformed into the shortest path adjacent matrix **A** as follows:

$$\mathbf{A} = \begin{bmatrix} 0 & d_{12} & \cdots & d_{1n} \\ d_{21} & 0 & \cdots & d_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ d_{n1} & d_{n2} & \cdots & 0 \end{bmatrix} \quad (2)$$

where, d_{ij} is the shortest path length between electrical node i and j.

III. MODEL OF DOUBLE-Q PLANNING FOR DISRIBUTION NETWORK

The characteristics of modern medium voltage distribution network are closed-loop design and open-loop operation. When the distribution network is in normal operation, the tie switch is open. When faults occurred, the tie switch is closed to supply power to the load.

Based on the abstraction of nodes and branches, the double-Q planning model of medium-voltage distribution network is to design a grid with the shortest feeders and the highest reliability to meet the electrical and topological constraints. The decision variables, objective functions and constraints in the distribution network planning model are as follows.

A. DECISION VARIABLES

The essence of distribution network planning is to optimize the connection between nodes. The decision variables of this model are as follows:

$$x_{ijk} = \begin{cases} 1, & \text{feeder } k \text{ is first connected to } i \text{ and then to } j \\ & i, j \in \Omega_L, k \in K \\ 0, & \text{otherwise,} \end{cases} \quad (3)$$

$$y_{ik} = \begin{cases} 1, & \text{feeder } k \text{ connected to } i \\ & i \in \Omega_L, k \in K \\ 0, & \text{feeder } k \text{ is not connected to } i, \end{cases} \quad (4)$$

$$B_{sk} = \begin{cases} 1, & \text{feeder } k \text{ is drawn from substation } s \\ & s \in \Omega_S,\ k \in K \\ 0, & \text{feeder } k \text{ is not drawn from substation } s, \end{cases} \quad (5)$$

where, x_{ijk} indicates whether feeder k is connected to load node i first and then to load node j. x_{ik} indicates whether feeder k supplies power to load node i. B_{sk} indicates whether feeder k is drawn from substation s.

B. OBJECTIVE FUNCTION

1) INVESTMENT COST

Based on the components described in Section II.A, the investment cost f_I mainly consists of the equivalent annual value of the investment cost on lines and switches, which is calculated by:

$$f_I = [\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{l} C_{\mathrm{I,t}}^{\mathrm{line}} x_{ijk} d_{ij} + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{l} C_{\mathrm{I,t}}^{\mathrm{equ}} x_{ijk}] \times \frac{r(1+r)^{\tau}}{(1+r)^{\tau}-1} \quad (6)$$

where, n is the total number of nodes in the network. l is the total number of feeders in the network. r is discount rate. τ is planning years. $C_{\mathrm{I,t}}^{\mathrm{line}}$ is the investment and construction cost per unit length of t-type lines, including overhead lines and cable lines. $C_{\mathrm{I,t}}^{\mathrm{equ}}$ is the investment and construction cost of t-type switch equipment, including sectional switches and switch cabinets.

2) MAINTENANCE COST

It is necessary to maintain distribution network. The annual maintenance cost of f_M mainly includes the maintenance cost of lines and switch equipment, which can be expressed by:

$$f_M = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{l} C_{\mathrm{M,t}}^{\mathrm{line}} x_{ijk} d_{ij} + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{l} C_{\mathrm{M,t}}^{\mathrm{equ}} x_{ijk} \quad (7)$$

where, $C_{\mathrm{M,t}}^{\mathrm{line}}$ is the maintenance cost per unit length of class t-type line, including overhead lines and cable lines. $C_{\mathrm{M,t}}^{\mathrm{equ}}$ is the maintenance cost of t-type switch equipment, including sectional switches and ring-network cabinets.

3) OUTAGE COST

In the current practice of distribution network planning, the reliability of distribution network can be objective function or constraint. If the reliability is regarded as a constraint, it only needs to be verified after calculation. However, it is necessary to take reliability as objective function in case of higher requirement for reliability. As we know, the topological connection of distribution network is closely related to its reliability. In order to accurately evaluate the economic losses caused by outages of different types of loads in distribution networks, Sector Customer Damage Function (SCDF) [18] and the outage time of load nodes obtained from reliability calculation are used to evaluate the annual power outage economic losses, which is written by:

$$f_R = \sum_{i=1}^{n} (\text{SCDF}_p(U_i) \cdot P_i) \tag{8}$$

where p is the type of the load node (including commercial, institutional, industrial, residential and other users, represented by types 1, 2, 3, 4 and 5 respectively). This paper assumes that breakers are only installed at the outlet of substations, and the other switches are sectional switches. Based on this assumption, the outage time U_i of all feeder load nodes can be obtained by using the reliability evaluation algorithm in [19]. P_i represents the peak load of electrical node i, which is obtained from the load forecasting module of digital platform.

C. CONSTRAINT CONDITION

1) TOPOLOGICAL CONSTRAINTS

In order to satisfy the topological constraints of open-loop operation in distribution network, the following conditions need to be satisfied:

$$\sum_{i=1}^{n}\sum_{k=1}^{l} x_{ijk} = 1, \quad \forall j \in \Omega_L \tag{9}$$

$$\sum_{k=1}^{l} y_{ik} = 1, \quad \forall i \in \Omega_L \tag{10}$$

$$\sum_{i=n_s+1}^{n} x_{ijk} = \sum_{u=n_s+1}^{n} x_{juk}, \quad \forall k \in K \tag{11}$$

In the above topological constraints, Equation (9) guarantees that each feeder can be only connected to a load node once. Equation (10) guarantees that each load node can be supplied by one group of feeders only instead of multiple groups of feeders. Equation (11) guarantees the continuity of the planned connection, i.e. the number of feeders with load node j as the first node is the same as that with load node j as the last node.

2) FEEDER CAPACITY CONSTRAINTS

The load of any feeder should not exceed the available capacity of the line, which is shown as follows:

$$\sum_{i=1}^{n} P_i x_{ik} \le \lambda\sqrt{3}U_k^e I_k^e \cos\varphi_k, \quad \forall k \in K \tag{12}$$

where, U_k^e is the rated voltage of feeder K. I_k^e is the rated current of feeder K. $\cos\varphi_k$ is the power factor of feeder K. When the connection mode is Single Ring Network (SRN), λ is set as 0.5. When the connection mode is two supplies and one backup (TSOB), the backup line usually does not carry load, so λ is set as 1.

3) NUMBER CONSTRAINTS OF SUBSTATION FEEDER

The number of feeders drawn from each substation should not exceed the maximum, which is written as follows:

$$\sum_{k=1}^{l} B_{sk} \le N_{s\max}, \quad \forall s \in S \tag{13}$$

where, $M_{s\max}$ is the maximum number of feeder lines allowed to be drawn from substation s.

4) CONNECTION MODE CONSTRAINTS

In order to achieve the closed-loop design, it is necessary to generate a closed-loop distribution network in line with connection modes. In the planning of distribution network, the choice of connection modes is very important, which has a great influence on the reliability of distribution network. Based on [20], this paper mainly models and analyzes three frequently-used connection mode units in urban 10kV distribution network, including Radial Network(RN), Single Ring Network(SRN), Two Supplies and One Backup(TSOB), as shown in FIGURE 3.

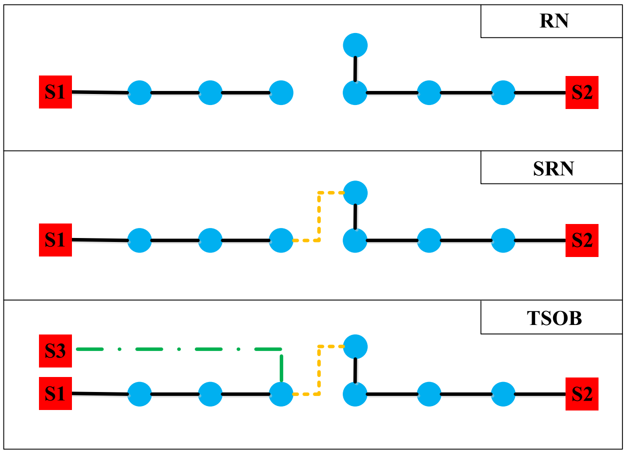

FIGURE 3. Schematic diagram of three common connection modes (Black solid lines represent regular lines, orange dotted lines represent tie lines, and green dash-dotted lines represent backup lines).

According to the characteristics of the connection mode in FIGURE 3, a closed-loop network can be generated by setting the connection of each feeder terminal node. The priority of the interconnection is as follows:

① Based on SPM, the terminal load nodes of feeders from different substations are interconnected until only one substation can draw out feeders.

② Based on SPM, the terminal load nodes of feeders from the same substation are interconnected until all feeders are interconnected or only one feeder is not interconnected.

③ Based on SPM, the terminal load nodes of each feeder are interconnected with the substation node, which has more remaining feeders available.

Different connection modes have different priority and the distribution network planning should be in the following order:

- If the connection mode is RN, it can be obtained by solving the above model directly.
- If the connection mode is SRN, on the basis of RN, make the connection first according to priority principle ①, and then according to priority principle ②.
- If the connection mode is TSOB, on the basis of SRN, make the connection in the order of ① ② ③.

D. MODELING

Based on the previous discussion, the objective function and constraints can form the following model:

$$\begin{aligned} &\min f_{\mathrm{I}} + f_{\mathrm{M}} + f_{\mathrm{R}} \\ &s.t.\ (9)(10)(11)(12)(13) \end{aligned} \tag{14}$$

This is a discrete optimization problem with multiple complex constraints. The decision variable is the connection between electrical nodes. If traversal algorithm is used, the time complexity of computation is $O(s^s(n-s)!)$, making it a typical NP-hard problem. When the problem contains a large number of discrete variables, it will cause the combination explosion problem and cannot be solved. Therefore, a suitable coding method and algorithm is the key to solve the model.

IV. SOLUTION OF DOUBLE-Q PLANNING FOR DISRIBUTION NETWORK

A. FITNESS FUNCTION DESIGN

Further analysis shows that reliability evaluation algorithms need to involve topological search and judgment, so the relationship between reliability and decision variables is difficult to be expressed as an explicit function. Since the established model is a discrete non-convex optimization model, it is hard to solve in classical mathematical methods (such as MIP algorithm).

Therefore, we employed the penalty function method [21] to transform the problem into an unconstrained optimization problem. The fitness function F is designed as follows:

$$F = f_{\mathrm{I}} + f_{\mathrm{M}} + f_{\mathrm{R}} + \eta N_p \tag{15}$$

where, N_p is the number of constraints that are not satisfied. η is penalty coefficient, which is set according to the objective function and constraints.

B. EAQ ALGORITHM

In the field of power system dispatching, such as AGC and GCD [29], there is a high demand for the efficiency of the algorithm. However, in distribution network planning, it is required to find the optimal solution as far as possible in finite time. Therefore, this paper presents an EAQ algorithm for solving this model.

1) THE RELATIONSHIP BETWEEN EAQ AND DISTRIBU-TION NETWORK PLANNING

Ant colony optimization (ACO) has obvious advantages in solving path search problems of graphs, while reinforcement learning(RL) is widely used in solving discrete optimization problems. Inspired by this, this study combines Q-learning (Q-learning is a typical algorithm in RL) with ACO, and integrates elite strategy to form a multi-agent collaborative learning framework. Table 1 shows the corresponding relationship between EAQ and distribution network planning.

TABLE 1. Correspondence between EAQ and distribution network planning.

Elements of EAQ	Elements in Distribution Network Planning
State r	The node connected by the current feeder is r
Action s	The feeder is connected from the previous node to the node s after the action is taken
Environment	Quantity and quality of the planning network
Memory matrix AQ	Historical gain records of different planning schemes
Reward function ΔAQ	The fitness function of distribution network planning （The visited node set is rewarded, otherwise it is not rewarded）
Elite Agent	m planning schemes with the minimum fitness value in each generation

2) CODING METHOD

From Section III.A, the model in this paper contains three types of 0-1 variables. It is easy to cause the dimension explosion problem when employing the 0-1 variable coding method to solve the large-scale node distribution network planning model, which makes it impossible to converge to the solution.

Inspired by TSP, this paper adopts sequence coding to represent the connection scheme of feeders. In this way, the solutions generated in the iterative optimization process are all ''feasible solutions'', which greatly improves the optimization efficiency. Take FIGURE 2 as an example. If a feeder is drawn from substation 2, and then connected to load node 10, 7, and 5, the coding sequence should be 2-10-7-5. At the same time, Tabu search table is introduced to record visited nodes to ensure that each load node is connected by only one feeder. Thus, the solution of each agent automatically satisfies the topological constraints (9) (10) (11), which greatly simplifies the large-scale complex optimization problems.

3) STARTING NODE ASSIGNMENT

In order to distribute the feeders from each substation reasonably, the roulette algorithm [22] is used to determine the initial power node position for all agents. The initial position of the agent is allocated in proportion to the number of feeders available in each substation. The formula is expressed as follows:

$$p_0^s = \frac{M_s}{\sum_{v \in S} M_v} \tag{16}$$

where, p_0^s is the probability of the agent being assigned to substation s. M_s is the number of feeders that can be drawn out from the current substation s.

When the feeder is connected to the next load node, the total load on the feeder exceeds the capacity of the feeder, namely, it is not satisfied (12). Similarly, based on (16), the starting node is selected, and the Tabu search table is used to continue to select the next load node.

4) ACTION SELECTION

The RL accumulates the rewards of all states-actions into the AQ matrix, which guides the agents to continue optimization.

Agent h generates the policy set of Generation k using the following state transition formulas:

$$s = \begin{cases} \arg\max_{u \in J_h(r)} \{[\boldsymbol{AQ}(r,u)]^\delta \cdot [\boldsymbol{HE}(r,u)]^\beta\}, & q \le q_0 \\ \text{Select node s according to equation(18)}, & q > q_0 \end{cases} \tag{17}$$

$$p^h(r,s) = \begin{cases} \dfrac{\boldsymbol{AQ}^\delta(r,s) \cdot \boldsymbol{HE}^\beta(r,s)}{\sum_{u \in J_k^h(r)} \boldsymbol{AQ}^\delta(r,u) \cdot \boldsymbol{HE}^\beta(r,u)}, & s \in J_k^h(r) \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

Equation (17) indicates that when the generated random number is less than q_0, the next load node is connected according to the Greedy Strategy. When the generated random number is greater than q_0, the next load node is selected according to the pseudo-random proportional rule of Equation (18). The value of the corresponding element is the reciprocal of the shortest distance calculated in Section II.C. J_h (r) is the complement set corresponding to the Tabu search matrix, representing the set of currently accessible electrical nodes of agent h.

5) MULTI-AGENT COLLABORATIVE LEARNING

When all agents complete feeder planning based on the above ε-greedy strategy, each agent exchanges information according to the fitness value F of environmental feedback, updates the AQ matrix, and achieves co-evolution, which is expressed as follows:

$$\boldsymbol{AQ}_h(r,s) \leftarrow (1-\alpha)\cdot \boldsymbol{AQ}_h(r,s) + \alpha[\Delta \boldsymbol{AQ}_h(r,s) + \gamma \cdot \max_{z \in J_k(s)} \boldsymbol{AQ}_h(s,z)] \tag{19}$$

$$\Delta \boldsymbol{AQ}_h(r,s) = \begin{cases} \dfrac{W}{F_h}, & (r,s) \in R \\ M\dfrac{W}{F_{gb}}, & (r,s) \in R_{gb} \\ 0, & Others \end{cases} \tag{20}$$

where, $\Delta \boldsymbol{AQ}_h$ (r, s) is the delay reinforcement part, which represents the gain brought by agents.

C. SOLUTION FLOW

In summary, EAQ-based distribution network planning is mainly divided into two parts. The first part uses AQ matrix and HE matrix to explore and optimize the formation of radial distribution network. The second part is to form a closed-loop network and get its fitness value based on the SPM and interconnection priority. Through multiple iterations, a synergistic optimal framework of economy and reliability is formed.

The specific steps of employing EAQ proposed in this paper to solve the double-Q planning of distribution network are shown in FIGURE 4.

V. CASES STUDY

A. DESCRIPTION OF PLANNING AREA

This study takes a newly-built business district of 2.1 square kilometers in Chinese urban area as an example for analysis. The voltage level of the distribution network to be planned is 10 kV. There are 12 horizontal and 16 vertical roads in the planning area.

YJV22-10/240 line is adopted in the planning area. By investigating the equipment price and engineering construction quotation in this area, the specific parameters are shown in TABLE 2.

TABLE 2. Planning parameters.

Parameter	Value
Capacity	435A
Cable line investment cost	$2150/km
Ring-network cabinets investment cost	$950
Cable line maintenance cost	$75 per/km
Ring-network cabinets maintenance cost	$45
line power factor φ_k	0.9

The planning life is 20 years and the discount rate is 10%. Reliability parameters of components are from [19]. The relationship between the power outage economic losses of various users and the power failure time are from [18]. The road network in the planning area is divided as shown in FIGURE 5. After simplifying the geographic information and load information obtained from GIS and SCADA, the total load is 372.63 MW, with 92 load nodes and 2 substation nodes S1 and S2, as shown in FIGURE 6. Other relevant data are shown in TABLE 1 and TABLE 2 of supplementary file A.

B. NUMERICAL EXAMPLE IMPLEMENTATION

1) COMPARISON AND ANALYSIS OF ALGORITHMS

To illustrate the effectiveness of the encoding method and algorithm presented above, Multiple coding methods and optimization algorithms are used to optimize the grid structure of the above medium voltage urban distribution network.

Repeated experiments show that it cannot converge in finite time when 0-1 variable is used. Further analysis of this encoding method shows that the optimization space size is at least 2^{167}, which cannot be converged due to the problem

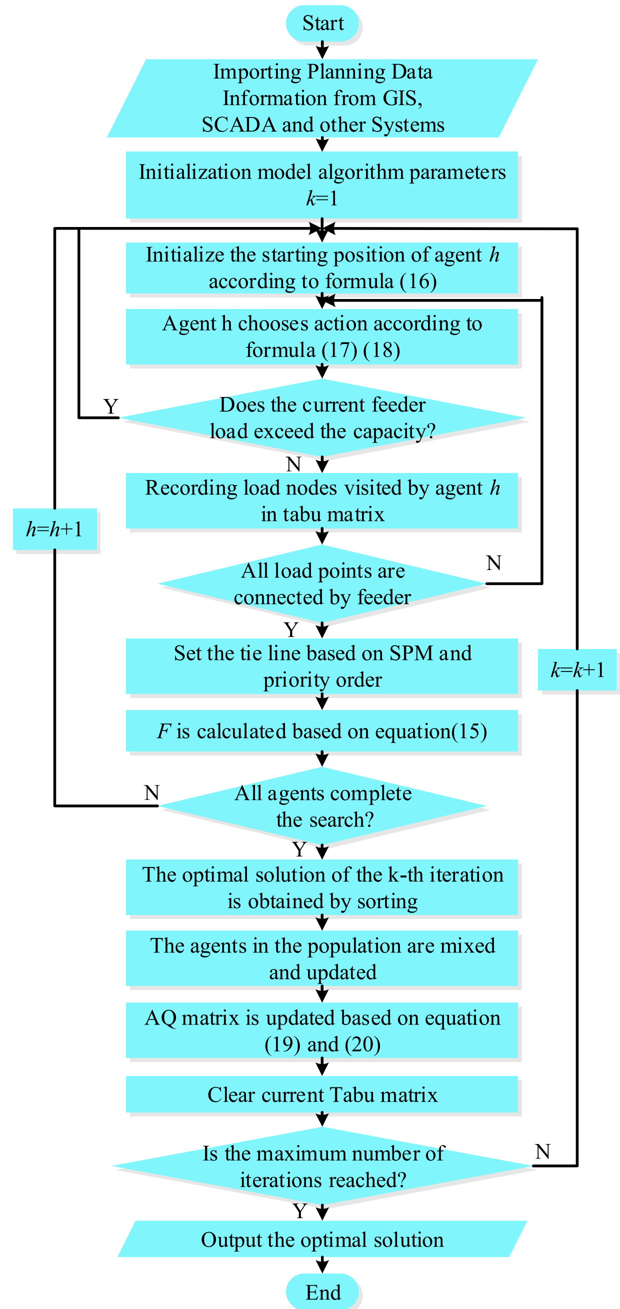

FIGURE 4. Flow chart of double-Q distribution network planning model based on EAQ.

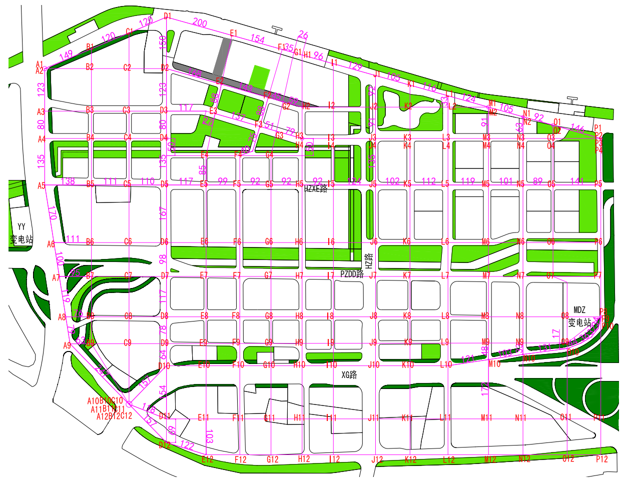

FIGURE 5. Road network division diagram.

of dimensionality curse [10]. Therefore, the following algorithm analysis uses sequence coding method for simulation calculation.

In order to highlight the advantages of this algorithm in solving topology related problems, this algorithm is compared with heuristic algorithms(GA, PSO) and meta-heuristic algorithms (such as GWO [24], TLBO [25], MVO [26], ALO [27], WOA [28]) In order to ensure the comparability between the algorithms, the population number N_A is set as 500, the maximum number of iterations N_c is set as 200, and the parameters are set by using the uniform design method [23]. Each algorithm were run 10 times and their results were compared and analyzed. The average value (Ave.), median (Med.), standard deviation (Std.), average convergence iterations (N_{con}) and average convergence time (t_{con}) are taken, as shown in the TABLE 3. The unit of fitness in TABLE 3 is thousand dollars. The sensitivity analysis of parameters is shown in supplementary file B. The parameter settings of different algorithms are shown in TABLE 1 of supplementary file C. All calculations are carried out in matlab-R2018a environment. The computer parameters are: kernel i7-7700, CPU3.60GHz, 8GB of memory.

Through the comparison of the latter three algorithms, it can be seen that in the same coding method, the EAQ proposed in this paper has obvious advantages over heuristic algorithms (GA, PSO) and meta-heuristic algorithms(GWO, TLBO, MVO ALO, WOA). The main reason is that GA employs global search strategy to explore solution space, which is blind and cannot effectively use distance information, resulting in low efficiency of the algorithm. Compared with GA, PSO is simpler and does not require crossover and mutation, while it is easy to fall into local optimum. Meta-heuristic algorithm is an improved heuristic algorithm (mainly evolved from SA, GA and PSO), which can solve many complex problems. It can solve general complex problems with fewer parameters. However, it is easily trapping in local optimum.

When employing EAQ, heuristic search is carried out according to the distance information between nodes. Meanwhile, agents exchange information through AQ matrix and use elite strategy to accelerate the convergence on while guaranteeing the convergence of the algorithm. Therefore, compared with other heuristic algorithms, the algorithm proposed in this paper can make better use of topological relations to optimize.

2) COMPARISON AND ANALYSIS OF SINGLE-Q PLANNING AND DOUBE-Q PLANNING

In order to verify the validity of the model in this paper, the following three cases are compared and analyzed.

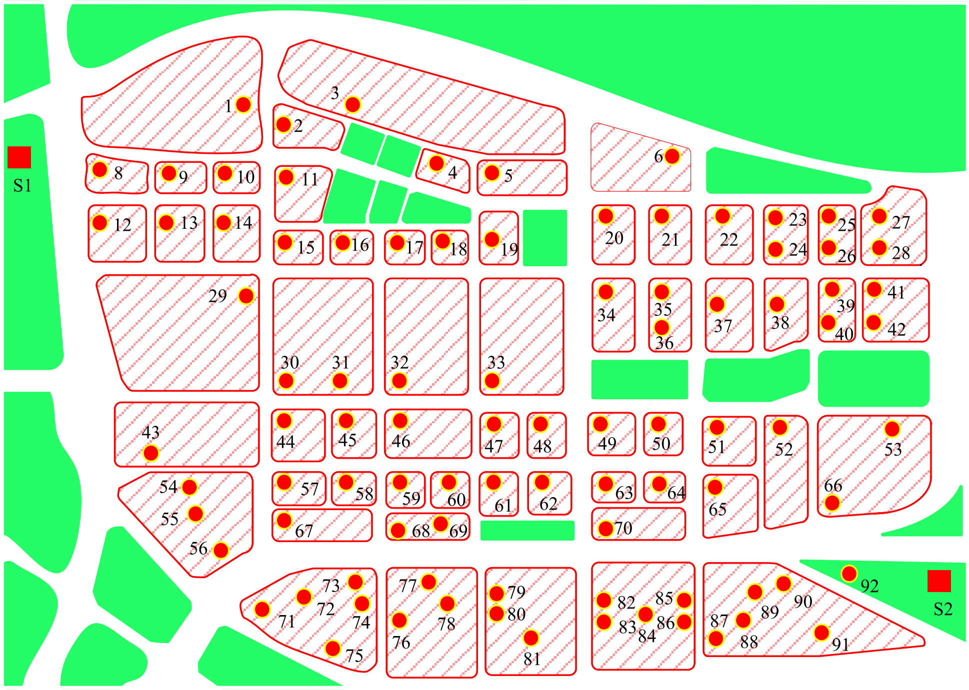

FIGURE 6. Schematic diagram of grid load nodes.

TABLE 3. Performance comparison between different algorithms.

Algorithm	Ave.	Med.	Std.	N_{con}	t_{con}
GA	292.56	292.68	7.1860	178.2	1275.5
PSO	301.47	302.69	9.8347	110.6	3655.9
GWO	290.76	291.07	5.0492	169.2	4917.3
TLBO	283.43	284.18	3.0511	93.3	3326.0
MVO	284.95	286.34	7.5695	167.0	6386.2
ALO	273.46	273.54	2.7985	112.9	4962.5
WOA	261.24	261.48	2.6384	66.4	2390.4
EAQ	**253.34**	**253.34**	**1.0896**	**39.8**	**229.3**

TABLE 4. Comparison between different cases.

Case	Comprehensive cost($)	Investment cost($)	Maintenance cost($)	Outage cost($)	SAIDI (hour/user)	SAIFI (times/user)	CAIDI (hour/user)	ASAI (%)
Case I	273.88k	102.90k	25.73k	145.27k	1.0508	3.0188	2.8741	99.9655
Case II	259.04k	103.76k	25.94k	129.34k	0.9890	2.8578	2.8891	99.9674
Case III	252.07k	104.86k	26.22k	121.00k	0.9900	2.8606	2.8892	99.9673

Case I: Single-Q planning, ignoring the reliability objective function, considering only economic function f_I and f_M.

Case II: Double-Q planning, considering f_I, f_M and f_R. The economic losses caused by power outages of different load types are the same (The power outage loss of all loads is \$3.22/kWh according to the grid standard).

Case III: Double-Q planning, considering f_I, f_M and f_R. The economic losses caused by different load types of blackouts are different.

Solving the above three cases with EAQ. The parameters of the algorithm are shown in TABLE 2 of supplementary file B. The optimal distribution network and corresponding evaluation indexes are obtained. The calculation index of different cases are shown in TABLE 4. The three optimal distribution network planning schemes in three cases are shown in TABLE 3, TABLE 4 and TABLE 5 of supplementary file A.

As can be seen from the TABLE 4, the comprehensive cost sequence of the three case is: Case I > Case II > Case III. The comprehensive cost consists of investment cost, maintenance cost and outage cost. It can be observed clearly from the FIGURE 9 that the investment cost and maintenance cost of the three cases are of little difference, while the outage cost

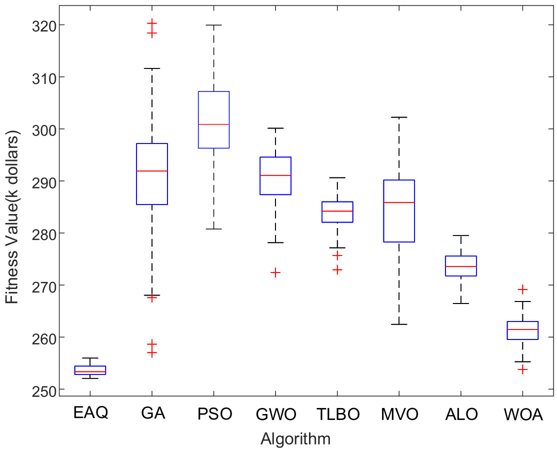

FIGURE 7. Box-and-Whisker plot of different algorithm.

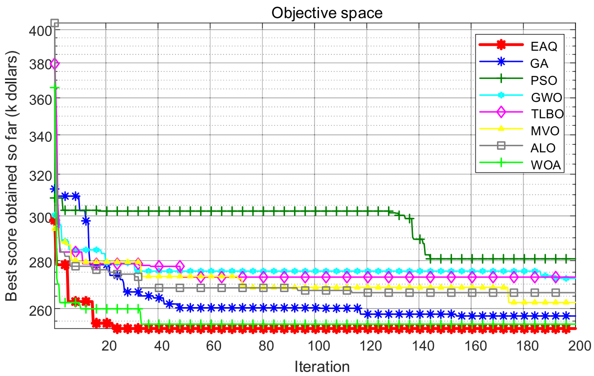

FIGURE 8. Convergence curve of different algorithms.

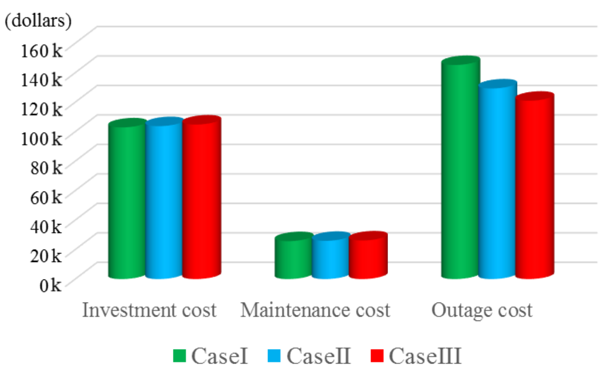

FIGURE 9. Comparation between different cases.

is quite opposite, which finally leads to the difference in the comprehensive cost. It can also be found that the reliability indexes are better in case II and case III than in case I. Therefore, applying double-Q planning can better coordinate the economy and reliability, and effectively improve the economic benefit of power grid in comparison with single-Q planning.

Comparing case II with case III, it can be seen that the reliability indexes of Case II are better than those of case III (SAIDI, SAIFI and CAIDI of Case II are lower than Case III, ASAI of Case II is higher than Case III). However, the comprehensive cost of building the distribution network in case II was 6.97k dollars higher than in case III. It can be concluded that economic losses caused by load blackout is relatively large when the planning area has high requirement for reliability. In particular, the economic loss caused by different types of load blackout is quite different. Therefore, blindly using reliability index to evaluate the reliability of distribution network cannot improve the comprehensive benefit of power grid company.

VI. CONCLUSION

This paper establishes a double-Q planning model for large-scale distribution network and solves it by employing the EAQ, which provides a novel idea for distribution network planning. By performing case studies on a newly-built planning area, we verified the practicality and effectiveness of the proposed model and algorithm. The numerical findings indicate that the algorithm we propose is more suitable to solve distribution network planning model than other heuristic algorithms, thanks to its feature of knowledge sharing and full use of topological structure. Furthermore, it can be found that double-Q planning can further improve the overall efficiency of distribution network planning, especially in the areas with high requirements for reliability.

The following contents will be further studied in the follow-up work of this paper:

- Establish large-scale distribution network planning considering uncertainties such as wind power generation, photovoltaic power generation, energy storage and other distributed energy.
- In this paper, the topological abstraction is only carried out for 2-1 single-ring network and TSOB. In the next step, the connection modes such as N-1 single-loop network and N-supply and M-backup need to be considered.
- The research results of this paper are a part of distribution network planning platform system. Load characteristic module and load forecasting module will be developed to form an integrated planning platform.

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ZIYAO WANG received the B.Eng. degree in electrical engineering from the South China University of Technology, Guangzhou, China, in 2019, where he is currently pursuing the M.S. degree with the School of Electric Power Engineering. His research interests include distribution planning and reliability assessment.

DAN LIN received the B.Eng. degree in electrical engineering from the South China University of Technology, Guangzhou, China, in 2018, where she is currently pursuing the M.S. degree with the School of Electric Power Engineering. Her research interests include distribution planning and reliability assessment.

GUANGXUAN ZENG received the B.Eng. degree in electrical engineering from the South China University of Technology, Guangzhou, China, in 2017, where she is currently pursuing the M.S. degree with the School of Electric Power Engineering. Her research interest includes cyber-physical system reliability assessment.

TAO YU (Member, IEEE) received the B.Eng. degree in electrical power system from Zhejiang University, Hangzhou, China, in 1996, the M.Eng. degree in hydroelectric engineering from Yunnan Polytechnic University, Kunming, China, in 1999, and the Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China, in 2003. He is currently a Professor with the College of Electric Power, South China University of Technology, Guangzhou, China. His research interests include nonlinear and coordinated control theory, artificial intelligence techniques in planning, and operation of power systems.