An Optimal Expansion Planning of Electric Distribution Network Incorporating Health Index and Non-Network Solutions

Zhou Limei, Sheng Wanxing, Liu Wei, and Ma Zhao

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***Abstract*—The health status of distribution equipment and network is not considered directly in the existing distribution network planning methods. In order to effectively consider the health status and deal with the risk associated with load and renewable generation uncertainties, this paper presents a new optimal expansion planning approach for distribution network (EPADN) incorporating health index (HI) and Non-Network Solutions (NNSs). HI and relevant risk are help to develop the optimal equipment replacement strategy and temporary NNSs are considered as promising options for handling the uncertainties of load growth, reliability requirements of power supply and output of distributed energy resources (DERs) at a lower cost than network alternatives. An EPADN model using network solutions (NSs) and NNSs is proposed. The planning objectives of the proposed model are safety, reliability, economy, and greenness which are the meaning of distribution network HI. A method integrating improved niche genetic algorithm (INGA) and spanning tree algorithm (STA) is fitted to solve the model presented here for real sized networks with a manageable computational cost. Simulation results of actual 22-node distribution network in China, illustrate the effectiveness of the proposed approach.**

***Index Terms*—distribution network planning, health index theory, reliability of power supply, distributed generation, demand response**

I. INTRODUCTION

AGING equipment is a widespread problem in the power grids of many countries. Aging assets not only cause the equipment performance to decrease but also bring substantial asset replacement costs. During the 1980s, Britain was the first to propose the idea of HI for electric power equipment in response to the mass-scale aging problem. HI is a single value to characterize asset condition and can be calculated based on the operation condition of field equipment and digital transformation of various equipment's information. HI on a scale of 0-10, 0 indicating the best condition, 10 the worst [1]. The HI-based electric power asset replacement strategy can comprehensively consider and quantify the important factors affecting asset replacement and give a more accurate analysis and diagnosis of power equipment's health status, especially suitable for forecasting and decision-making of electric power asset replacement number in the short- and medium-term [2].

The traditional distribution network planning method in China basically didn't consider health state of equipment. For the distribution network was designed to meet the high load growth and most devices were almost new at that time. But health state of equipment must be considered after 30 or 40 years and equipment replacement decision problem should be studied using scientific theory and method in order to improve asset utilization, return on investment and reliability cost benefit. The CIGRE report also pointed out that grid planning must take into account some important assets probably reaching their life expectancy [3].

Furthermore, the investment cost of distribution networks is over 58% of the construction investment cost of 750kV and below power grids in China during the 12th five-year plan, reflecting a large investment in distribution networks to meet increasing peak demand, to replace aging assets, and to meet higher reliability standards. In addition, renewable energy targets are set by nations to develop a rapid uptake of green energy sources, for example, 27% contribution of renewables by 2020 in China's electricity generation [4]. Therefore, it is expected this investment situation becomes worse as more and more variable generation are integrated within distribution networks. This is because distribution requires additional network capacity to tackle the uncertainties of variable renewable sources and load forecast. While the temporary NNSs like demand response (DR) and generation curtailment (GC) are considered as a promising option to manage risks arising from load and renewable generation uncertainties. It can save or delay investment cost of distribution networks. With increased uncertainties in the system, a novel EPADN incorporating HI and NNSs is required, enabling network

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planners to make informed decisions on network augmentation in the most cost-effective manner.

The distribution expansion planning methods have been a topic of interest over last four decades and domestic and foreign scholars have proposed many methods used to solve distribution network planning problems, such as the traditional planning method [5,6], reliability based planning method [7~9], active distribution system (ADS) planning method [10-11] and the planning method integrating asset management [12], and so on. In traditional planning methods for distribution network, power supply reliability is implicitly reached by "N-1" criterion, usually taking minimum total cost as planning objective and without consideration of the cost of expected energy not supplied (EENS) and reliability cost benefit. The deterministic "N-1" criterion only considers the consequences of "N-1", but ignores its probability. The factors considered in the method often are network topology, capacity margin and power supply capability or load transfer capability and so on, basically without consideration of the impact of asset aging. In reliability-based planning methods of distribution network, probability of failure (POF) is actually considered. But POF is not accurate due to lack of statistical failure data, leading to inaccurate prediction and evaluation results of power supply reliability. Therefore, it is difficult to reflect the health status of equipment by POF. Although the ADS planning method considers uncertainty and volatility of DERs, but doesn’t consider the health condition of equipment. The risk of EENS is considered based on the balance of power supply reliability and cost in the distribution network planning method integrating asset management in which HI isn’t considered directly either.

In this context, an EPADN integrating HI, reliability of power supply and renewable energy interconnection is developed in the paper to enable utilities to plan their networks at a lower cost and treat the risk of load and renewable uncertainty through NNSs. This planning method inherits the advanced concept of reliability-based distribution network planning, the ADS planning and asset management. It can help to develop scientifically and accurately the optimum equipment replacement and renovation strategy, make reliability prediction and evaluation more accurate and provide a quantitative analysis basis for DERs interconnection based on HI. Therefore, the proposed method solves the weakness of traditional planning and the uncertainty of DERs output, saves or delays the investment cost of distribution network, and improves economic and social benefit as well as management level of distribution network. The relationship between EPADN and other planning methods is shown in Figure 1.

Accordingly, a novel EPADN model with safety, reliability, economy and greenness as planning objectives is established to find the optimal network planning scheme which satisfies load growth, reliability requirements and the constraints such as branch capacity and node voltage, and so on. At the same time, a method integrating improved niche genetic algorithm (INGA) and spanning tree algorithm (STA) is fitted to solve the model presented here for real sized networks with a manageable computational cost. Simulation results of actual 22-node distribution network in China, illustrate the effectiveness of the proposed approach.

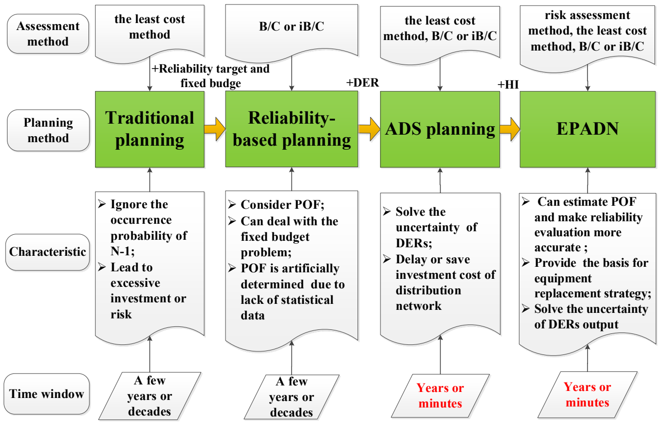

Fig. 1. The relationship between EPADN and other planning methods.

This paper is organized as follows. The next section gives detailed description of EPADN method integrating HI and NNSs. This is followed by section three which presents the problem formulation of EPADN. Section four proposes an efficient solution approach for EPADN. The simulation results are provided in section five. Finally, section six presents the relevant conclusions.

II. PLANNING METHOD INTEGRATING HI AND ACTIVE MANAGEMENT

A. Planning Content

The EPADN includes two parts, the capacity planning and the non-capacity planning, as shown in Figure 2.

In capacity planning, new lines are built to meet the new load points. In a planning year, the number of new load points is forecasted. The number of new lines depends on the number of new load points and the network structure. The sizing of the new lines depends on the peak load of the new load points and the grid structure. It is necessary to strike the right balance between the investment in large-section wires and the cost of DR. Given the forecasted load growth, small cross-section wires are not expected to be used in future. Initially, a slow load growth and a high distributed generation (DG) output may cause an over-voltage problem. In case of over-voltage, on-load tap changer (OLTC) transformers or voltage regulators (VRs) may be deployed to avoid GC. With the load growth of the existing load points, it is necessary to judge whether the existing lines meet technical constraints, such as capacity and voltage constraints. If an overload occurs, three types of planning measures are considered: 1) construction of new lines and re-sizing of branches; 2) using DR; and 3) active power support by DG units. When the voltage falls below the lower threshold, three types of planning measures are considered: installing VRs or capacitors, using DR and providing reactive power support by DG units.

In the non-capacity planning, four types of equipment (transformers, switches, overhead lines and cables) that are in a very poor state ($7 < \mathrm{HI} \leqslant 10$) are replaced by new equipment

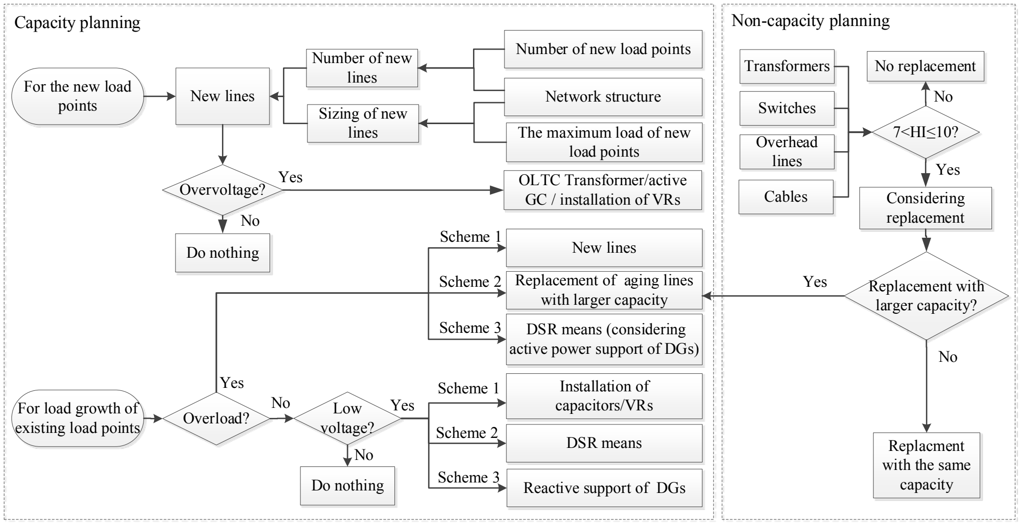

Fig. 2. The content of distribution network expansion planning integrating HI and NNSs.

with at least the same capacity (sometimes with larger capacity because of the load growth). Table 1 shows the classification of HI grades [13]. Finally, whether the equipment should be replaced depends on the risk planning results of the distribution network.

TABLE I
CLASSIFICATION OF HI GRADES

HI scores	Health state	Color
0<HI⩽3.5	Excellent	Green
3.5<HI⩽5.5	Good	Pale Blue
5.5<HI⩽7	Poor	Yellow
7<HI⩽10	Very poor	Red

B. Planning process

The EPADN considers the equipment operation status and the current and forecasted status of the equipment. It combines with the HI evaluation, risk assessment and active management solutions. The concrete planning process (see Figure 3) is presented as follows:

(1) Set planning objectives. Determine distribution network planning objectives for a planning target year., e.g. a target power supply reliability of 99.999%.

(2) Data acquisition & processing. The data to be acquired include network topology data, line parameters, generator outputs, the load profile of each node, power flow parameters, reliability parameters, equipment costs, power losses, core sets of indicators for health assessment and so on.

(3) Current and future HI assessment of the assets and the network. In the HI calculation formulas proposed by EA technology, HI obeys the exponential law. However, the actual health state of the equipment is affected by not only aging but also other factors such as the operation environment and maintenance. In this paper, the correction factors are used in the HI calculation formulas.

$$HI(t) = HI_1 \cdot \prod_{i=1}^{4} \alpha_i(t) \tag{1}$$

Where $HI(t)$ is the final HI and $\alpha_i(t)$ is the correction factor, which accounts for the insulating state, operation environment, maintenance records and auxiliary state. The calculating method of $\alpha_i(t)$ sees reference [13]. HI_1 is formulated as:

$$\boldsymbol{HI_1 = HI_0} \times \boldsymbol{e^{B(T_2-T_1)}} \tag{2}$$

Where HI_0 is the initial HI of the equipment when first coming into service, normally assigned a value of 0.5 based on experts' experience [13]. HI_1 is the aging HI of the equipment in the current or any forecast year. B is the aging coefficient, depending on the expected service life. T_1 and T_2 are respectively the year corresponding to HI_0 and HI_1. Reference [14] presents a range of other methods for the HI calculation for equipment and the distribution network [14].

POF has an exponential relation with the HI, as given by

$$\lambda_{POF} = K \times e^{HI \times C} \tag{3}$$

Where K and C are respectively the scaling factor and the curvature factor.

(4) Analyse the weak links of the current distribution network. Find the weak links of the current network by applying the HI assessment, power flow analysis, N-1 analysis and the power supply reliability evaluation. They collectively lay the foundation for developing planning schemes.

(5) Load forecast and classification. Carry out load forecast for the planning target year and then determine the load growth of new and existing load points. Loads can be divided into uncontrollable loads and controllable loads based on the controllability. The controllable loads can be further divided into interruptible loads and transferable loads, where the transferable load is further divided into responsive loads and non-responsive loads. The interruptible loads and responsive loads are classified as friendly loads, as shown in Figure 4.

The greater the proportion of friendly loads, the higher the degree of active control in the distribution network. The total load L is formulated as:

$$L = L_1 + L_2 + L_3 \tag{4}$$

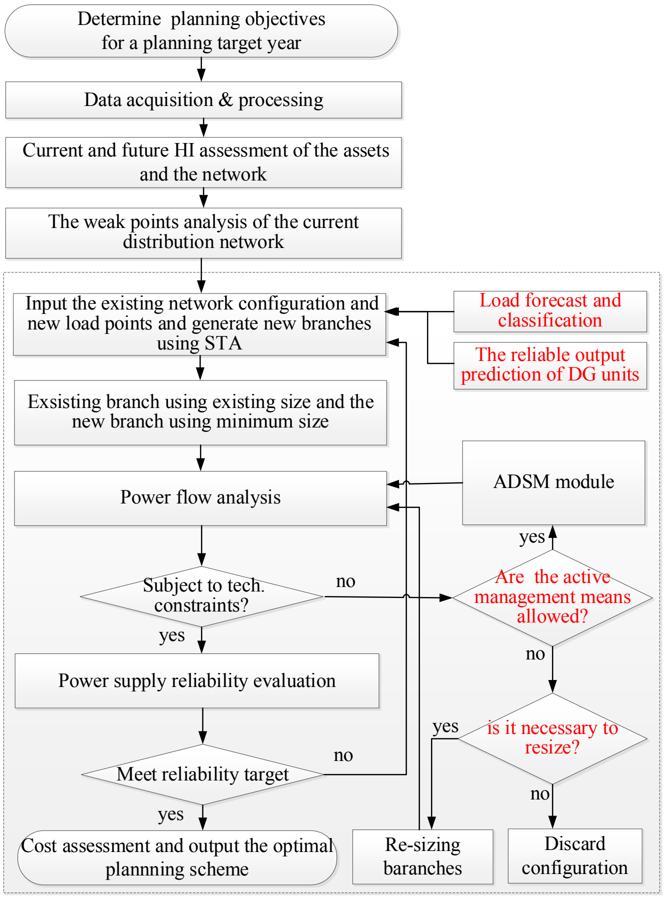

Fig. 3. The process of EPADN integrating HI and NNSs.

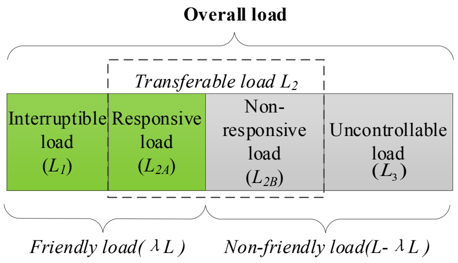

Fig. 4. Load classification.

in which L_1, L_2 and L_3 denote respectively the interruptible load, transferable load and uncontrollable load.

The active control factor τ is formulated as:

$$\tau = \frac{L_1 + L_{2A}}{L} \times 100\% \tag{5}$$

in which L_{2A} is the response load.

(6) The reliable output forecast of DG units. Select typical days of the four seasons and calculate the reliable DG output for each typical day using the input data such as the total installed capacity, typical daily output curve and output confidence. The reliable output is that DG can at least achieve the output level within a certain probability (confidence level). For example, $P_{DG\_n}^{90\%}$ represents that the probability of the DG n output exceeding $P_{DG\_n}^{90\%}$ is 90%. $P_{DG\_n}^{\beta}$ is derived from the probability density function (PDF) or cumulative distribution functions (CDF) of the DG outputs.

(7) Input the existing network configuration and new load points and generate new branches using STA. For new load points, a practical Mayeda spanning tree method based on the matrix exclusive or operation [15] is used to form alternative planning schemes to ensure the connectivity and the radial topology of the network. The tie lines are planned according to the shortest path principle and planning objectives, such as reliability target.

(8) The sizes of existing branches remain unchanged and the minimum sizes are chosen for new branches. For each configuration examined and before cost calculation, the suitable conductor sizes for all branches are chosen, taking into account all technical constraints, the planning horizon and both the normal operation and emergency states.

(9) Power flow analysis. In power flow analysis, loads and generators are modelled as constant current nodes.

(10) Check the technical constraints. If they are violated, we try to determine the proper cross-section for each conductor and then go to the previous step. If no proper cross-section can be found, discard the configuration. If the active management means are allowed, active distribution system management (ADSM) module will be executed, shown in Figure 5.

(11) Power supply reliability evaluation. Power supply reliability of the network configuration is forecasted according to HI and POF in the planning year. If the result meets reliability target, cost assessment is required and the optimal planning scheme is output. Otherwise, turn to the step (7) and regenerate new branches using STA.

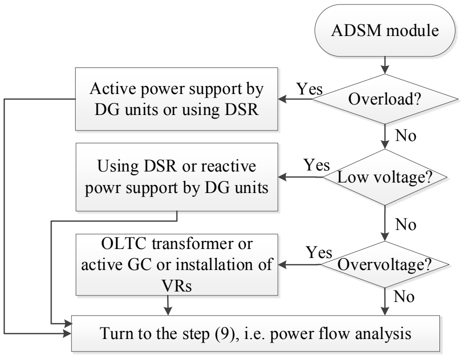

Fig. 5. The flow chart of ADSM module.

III. 3. PROBLEM FORMULATION

A. *Objective Function*

According to the meaning of distribution network HI [14], the planning objectives of distribution network can be summarized as four aspects: safety, reliability, economy and greenness.

(1) Safety risk refers to personal injury and load not transferred caused by hidden danger, including personal safety and power supply safety. We must guarantee personal safety, but it is difficult to quantify. Power supply safety is mainly the load transfer capability that is one of the necessary conditions to guarantee reliability. So the load transfer capability is implied in the reliability target, see constraint 7).

(2) The reliability risk R_r mainly refers to the loss of EENS caused by unreliability, including two aspects, i.e. reliability of

power supply and voltage quality. The power supply reliability is mainly the annual loss of EENS C_F^t and voltage quality is mainly voltage drop, expressed as the constraint 4).

(3) The economic risk R_e refers to the total cost caused by the new construction, reinforcement, operation and maintenance of distribution network, expressed as separately C_I, C_R, C_O^t *and* C_M^t. The DG units or distributed energy storages (DESs) are invested and constructed by the independent investors, so their purchase and installation costs are not considered.

(4) The greenness risk R_g refers to the cost of providing support for distribution network by means of DERs, including the annual cost of using DR means C_{DSR}^t, the annual cost of active power GC $C_{DG\_P}^t$ and the annual cost of providing reactive power support by DGs $C_{DG\_Q}^t$.

Therefore, the mathematical model of EPADN is described as follows:

$$\min R = R_e + R_r + R_g \tag{6}$$

In which,

$$R_e = (C_I + C_R) + \sum_{t=0}^{Y-1} \frac{1}{(1+i)^t} (C_O^t + C_M^t) \tag{7}$$

$$R_r = \sum_{t=0}^{Y-1} \frac{1}{(1+i)^t} C_F^t \tag{8}$$

$$R_g = \sum_{t=0}^{Y-1} \frac{1}{(1+i)^t} \left(C_{DSR}^t + C_{DG\_P}^t + C_{DG\_Q}^t\right) \tag{9}$$

In the formula (7) ~ (9), Y is the life cycle of distribution network and i is the discount rate. Other variables are the following:

1) The investment cost of new feeders C_I

The investment cost of new feeders includes the cost of equipment purchase, design and installation, and so on. The expression of C_I is as follows:

$$C_I = \sum_{k\in b(l)} C_{I\_k} l_{I\_k} x_k \tag{10}$$

Where,

$b(l)$ ——The set of new medium-voltage (MV) branches;

l_{I_k}——The length of new branch k (km);

C_{I_k}—— The comprehensive investment cost per km of new branch k (yuan/km);

x_k——The decision variable. If the branch k will be built, x_k equals 1,otherwise x_k equals 0;

2) The investment cost of replacing equipment C_R

The investment cost of replacing equipment includes the cost of removing old equipment and procurement, design and installation cost of new equipment. The expression of C_R is as follows:

$$C_R = \sum_{k\in r(l)} l_{R\_k} C_{R\_k} y_k \tag{11}$$

Where,

$r(l)$ ——The set of equipment to replace, including MV branches, switches and high-voltage transformers in a very poor state ($7 < HI_k \leq 10$) at the planning level year.

l_{R_k}——The mumble or length of equipment k to be replaced;

C_{R_k}——The comprehensive replacement investment costs per unit of equipment k;

y_k —— The decision variable. if the equipment is replaced, y_k equals 1, otherwise y_k equals 0.

3) The annual operating cost of distribution network C_O^t

The operating costs of distribution network mainly includes line loss and transformer loss. The transformer loss is less related to the structure of distribution network. Therefore, only line loss is considered. The expression of C_O^t is as follows:

$$C_O^t = \sum_{k\in(u(l)\cup b(l))} z_k C_p \tau_{max,k} R_k \frac{{P_k}^2 + {Q_k}^2}{{V_k}^2} \tag{12}$$

Where,

$u(l)$ ——The set of current branches;

$b(l)$ ——The set of new branches;

z_k—— The parameter used to reflect whether the branch k is included in the planning scheme. If $z_k = 1$, the branch k is included; otherwise, the branch is not included.

C_p—— The electricity price;

$\tau_{max,k}$——The maximum load loss hours of branch k;

R_k—— The resistance of branch k;

P_k—— The active power of branch k;

Q_k—— The reactive power of branch k;

V_k—— The node voltage amplitude of branch k.

4) The annual maintenance cost of distribution networks C_M^t

The maintenance cost of distribution network refers to the cost of equipment failure and maintenance personnel and so on. The expression of C_M is as follows:

$$C_M^t = (C_R + C_I)\lambda \tag{13}$$

where λ——The maintenance rate of distribution network.

5) The annual cost of reliability risk C_F^t

The cost of reliability risk refers to the cost of EENS. It is given by formula (14).

$$C_F^t = d_S \times P_{EENS} \tag{14}$$

Where,

d_s——The outage cost per energy. There are three ways to calculate d_S [16] and the method based on gross domestic product (GDP) was used here.

P_{EENS}——The EENS.

$$P_{EENS} = \sum_{k\in(u(l)\cup b(l))} z_k \lambda_k l_k \left(\sum_{i=1}^{N_{loc\_k}} P_i \cdot t_{loc\_k} + \sum_{i=1}^{N_{iso\_k}} P_i \cdot t_{iso\_k} + \sum_{i=1}^{N_{rep\_k}} P_i \cdot t_{rep\_k}\right) \tag{15}$$

Where,

l_k——The length of branch k (km);

N_{loc_k}, N_{iso_k} and N_{rep_k}——The number of outage load points or customers during the period of fault location, fault isolation and repair;

t_{loc_k}, t_{iso_k} and t_{rep_k}——The fault locating time, isolation time and repair time of branch k;

P_i——The load value of load point or customer i;

z_k ——Reflect whether the branch k is included in the planning scheme, if $z_k = 1$, branch k is included; Otherwise, it is not included;

λ_k——The failure rate of branch k, which has an exponential relationship with equipment HI, see formula (3).

6)The annual cost of greenness risk R_g

The annual cost of greenness risk mainly includes three parts. Their formulas are as follows:

$$C_{DSR}^t = \sum_{n=1}^{N_{DSR}} \alpha_n U_{DSR\_n} S_{DSR\_n} \tag{16}$$

S_{DSR_n}——The total curtailed electricity consumption of customer n participating in DR；

U_{DSR_n}——The consumption compensation fee per unit (kWh) of customer n participating in DR;

$\mathrm{N_{DR}}$——The number of customers involved in DR;

α_n——The decision variable. If the customer *n* participates in DR, α_n=1; otherwise α_n=0.

$$C_{DG\_P}^{t} = \sum_{n=1}^{N_{DG\_g}} \beta_n U_{DG\_pn} S_{DG\_pn} \qquad (17)$$

S_{DG_pn}——The generation losses of DG *n* due to GC;

U_{DG_pn}——The compensation fee per unit (kWh) of DG *n*;

$\mathrm{N_{DG\_gc}}$——Total number of controllable DG units;

β_n——The decision variable. If output of DG *n* is curtailed, β_n=1, otherwise β_n=0.

$$C_{DG\_Q}^{t} = \sum_{n=1}^{\mathrm{N_{DG\_gc}}} \gamma_n U_{DG\_qn} S_{DG\_qn} \qquad (18)$$

S_{DG_qn}——The reactive power generation capacity of DG *n*;

U_{DG_qn} ——The cost of purchasing reactive power generation capacity per unit (kVarh) of DG *n*;

$\mathrm{N_{DG\_gc}}$——Total number of controllable DG units;

γ_n——The decision variable. If DG *n* provides the reactive support, γ_n=1; otherwise γ_n=0.

B. Constraints

1) Power balance constraints

$$\begin{cases} P_{Gi} - P_{Li} = P_i, \ i = 1,2,\cdots,N \\ Q_{Gi} - Q_{Li} = Q_i, \ i = 1,2,\cdots,N \end{cases} \qquad (19)$$

where the P_{Gi} and Q_{Gi} are respectively active and reactive generation power at the node *i*; P_{Li} and Q_{Li} are respectively active and reactive loads at the node *i*; $P_i$and Q_i are respectively the amount of active and reactive injection at the node *i*; N_s is the total number of nodes.

2) Branch power flow constraint

$$S_{ij} \le S_{ijmax}, \ k = 1,2,\cdots,N_L \qquad (20)$$

where S_{ij} and S_{ijmax} are respectively the apparent power and maximum allowable apparent power of the branch from node *i* to node *j*.

3) Node voltage constraint

$$U_{jmin} \le U_j \le U_{jmax}, \ \mathrm{j} = 1,2,\cdots,N_s \qquad (21)$$

Where U_j is the voltage amplitude of node *j*, U_{jmin} and U_{jmax} are respectively the upper and lower limits of voltage amplitude of node *j*.

4) Voltage drop constraint

$$U_{kmin} \le \Delta U_k \le U_{kmax}, \ i = 1,2,\cdots,N_L \qquad (22)$$

Where ΔU_k is the voltage drop on the feeder *k*, U_{kmax} and U_{kmin} are respectively the maximum and minimum allowable value of voltage drop on feeder *k*. According to reference [17], the value is taken ±7%.

5) The reliable DG output constraint

$$P_{DG\_n}^{min} \le P_{DG\_n}^{\beta} \le P_{DG\_n}^{max}, n = 1,2,\cdots,N_{DG} \qquad (23)$$

$$Q_{DG\_n}^{min} \le Q_{DG\_n}^{\beta} \le Q_{DG\_n}^{max}, n = 1,2,\cdots,N_{DG} \qquad (24)$$

$P_{DG\_n}^{\beta}$, $Q_{DG\_n}^{\beta}$——The active and reactive power reliable output of the *n*th DG;

$P_{DG\_n}^{max}$, $Q_{DG\_n}^{max}$——The maximum active and reactive power output of the *n*th DG respectively;

$P_{DG\_n}^{min}$, $Q_{DG\_n}^{min}$——The minimum active and reactive power output of the *n*th DG respectively;

6) Load shedding constraint

$$0 \le P_{DSR\_m} \le P_{DSR_m}^{max}, \ m = 1,2,\cdots,\mathrm{N_{DR}} \qquad (25)$$

$P_{DSR\_m}^{max}$——The upper limit of load shedding for the *m*th customer which participated in DR;

P_{DSR_m} ——The amount of load shedding for the *m*th customer which participated in the DR.

7) Reliability target constraint

$$RS \ge RS_O \qquad (26)$$

Where RS is the actual average service availability index (ASAI) in the planning year; RS_O is the target value of ASAI.

IV. SOLUTION APPROACH

The objective function is non-linear in the formula (6), because power loss is a quadratic function of line transmission power and the formula (19) is the non-linear constrains. Thus above-described model is a non-linear mixed integer programming model. A method combining INGA and STA is proposed to solve the EPADN model. Compared with standard genetic algorithm (SGA), INGA increases the population diversity and can jump out of the local optimization, with high global search ability and convergence speed, especially suitable for solving more complicated multi-variant and multi-modal problems. Mayeda STA based on matrix exclusive or operation is with the characteristic such as completeness, non-redundancy and fast calculation. A combination of both can play the advantages of two kinds of algorithms to improve the solution quality and efficiency.

The flowchart of INGA is presented in Figure 6. Based on the characteristics of EPADN, some improvements, such as encoding mode, genetic operators and converge condition are made as follows:

(1) Input system data, parameter values and variable values. The input parameters of INGA include the maximum iterations, the chromosome population size, crossover rate, mutation rate and the constants used to calculate the fitness function values.

(2) Form chromosomes with binary coding. The new branches to be built, the equipment to be replaced and NNSs (DR, GC and reactive power support by DG units) to be selected will be encoded by binary coding, making up the chromosome together. If any new branch is built or any equipment is replaced or any NNS is adopted, the coding value equals 1. Otherwise, the value equals 0. The length of each chromosome should equal the sum of the number of new branches to be built, equipment to be replaced and NNSs to be selected. Each chromosome presents a network planning scheme (see Figure 7).

(3) Generate randomly initial population. The initial population is composed of *N* chromosomes. For the new load nodes, alternative new-built planning schemes are developed by practical Mayeda spanning tree method based on matrix exclusive or operation in order to satisfy the network connectivity and radiation constrain. For the existing distribution network, the set of equipment to be replaced is determined according to HI (7<HI≤10).

(4) Two-point mutation operation. In order to improve planning schemes, two-point mutation operation is adopted. This means another more economical new line joins the network once a new line is removed.

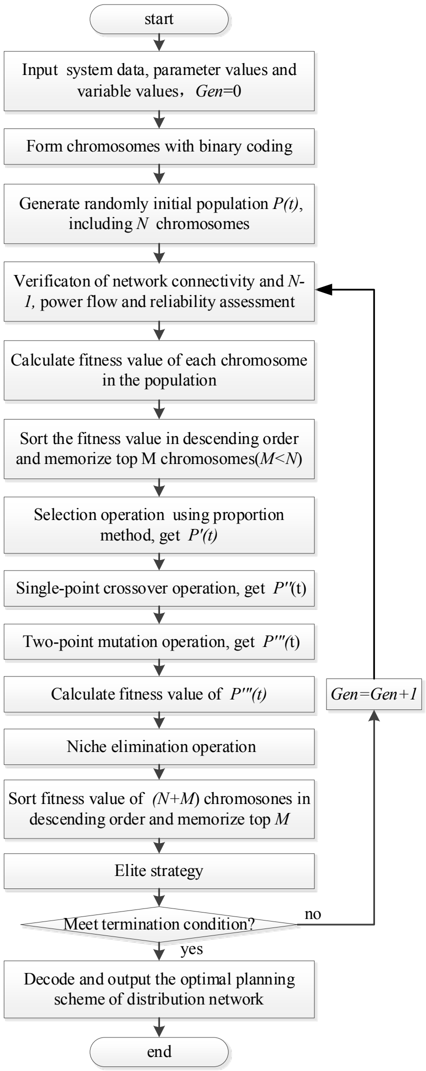

Fig. 6. INGA flowchart.

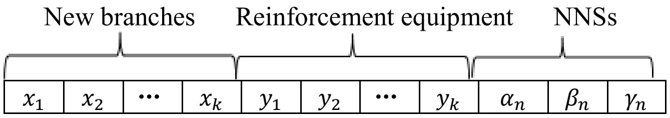

Fig. 7. Chromosome structure in INGA.

(5) Niche elimination operation. N chromosomes after mutation and top M chromosomes will be merged together and a new population will be got. Then for theses (N+M) chromosomes, the Hamming distance between two individuals X_i and X_j is as follows:

$$\|X_i - X_j\| = \sqrt{\sum_{k=1}^{N}\left(x_{ik} - x_{jk}\right)} \tag{27}$$

$$(i = 1,2,\cdots,N+M-1; j = i+1,\cdots,N+M)$$

When $\|X_i - X_j\| < L$, the fitness values of X_i and X_j are compared and the individual with lower fitness value will be punished by the penalty function [18]. Where L is the average of Hamming distance between all individuals. The $\|X_i - X_j\|$ may be changed with the development of evolution, therefore L should be changed dynamically to ensure the diversity of population. L is set as dynamic function:

$$L = L/t \tag{28}$$

Where t is the number of generations.

(6) Elite strategy. The ratio of individuals with optimal-adaptive value is usually between 10% and 15% in distribution network optimal planning problems.

V. 5. THE SIMULATION RESULTS

A. 5.1. *Case introduction*

The paper takes eight 10kV lines (five overhead lines and three cables) of a substation (110/10kV, 2×40MW) suitable DERs integration as the basic structure in reference [19]. The case includes three types of regions, i.e. rural area, town and downtown, and three typical configurations, i.e. radiation, multi-zone and ring, reflecting the actual situation of distribution network in China. The network structure is shown in Figure 8.

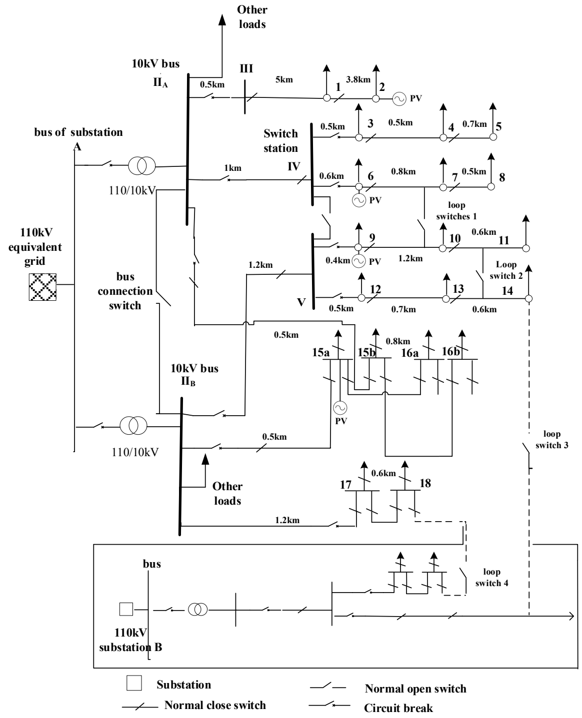

Fig. 8. The basic structure of test system.

At present, power supply area of distribution network is about 3.1km^2. The maximum load in 2016 was about 24MW. In which commercial load was 16.85MW, accounting for 70% of the total load. The residential load was 7.22MW, accounting for 30%. The load density and ASAI were about 7.42MW / km^2 and 99.995% separately in 2016.

The target of power supply reliability in 2021 will be 99.996%. The average annual load growth rate of the existing load points in this region is 4% [20]. Due to the rapid growth in town areas, there will be six load points, with about 5 MW in total, as shown in Table 2 [21]. There are no new load points in the downtown and rural areas. Thus, the maximum total load will be about 34.28 MW in 2021.

TABLE 2
NEW LOAD POINTS BY 2021

Symbol	Apparent power (kVA)		Total(Consider power factor and simultaneous rates)(kW)
	Residential	Commercial	
19	400	1000	882

20	300	800	693
21	700	1500	1386
22	280	7601	655.2
23	700	0	441
24	0	1500	945
total	2380	5560	5002.2

The position and capacity of friendly loads in 2021 are shown in Table 3. The friendly load nodes are 2, 5, 8, 11, 17 and 18, which can remove all of their load to deal with the emergency state of distribution network. The total friendly load is 7.49MW, accounting for 21.85%. The installed capacity of PVs on node 2, 6 ,9 and 15a in 2021 will be separately 1MW, 1MW, 1MW and 2MW. So the ratio of total installed capacity and maximum load will be 14.49%. The confidence degree of PV output β during peak load times is 90%. The peak load curve and PVs output curve in the summer of 2021 are shown in Figure 9.

TABLE 3

THE POSITION AND CAPACITY OF FRIENDLY LOADS IN 2021

Node number	power(kW)	The ratio of friendly load and maximum load (%)
2	1054	3.07%
5	1180	3.44%
8	1054	3.07%
11	548	1.60%
17	1323	3.86%
18	2331	6.80%
total	7490	21.85%

Assuming that the life cycle of distribution network is 20 years and the discount rate is 2.25%, i.e. $Y = 20$ and $i = 2.25\%$ [22]. The relevant parameters in INGA are shown in Table 4. The HI, POF and average repair time of each type of equipment are shown in Table 5 and Table 6. POF is calculated by the formula (3) based on equipment HI and historical statistics of utilities in State Grid Corporation of China (SGCC). The comprehensive cost and other parameters in the model of 10kV branches are shown in Table 7 and Table 8. Table 5 to Table 8 are shown in appendices.

TABLE 4

INGA PARAMETERS

Parameters	Value	Parameters	Value
The initial population scale of chromosomes	60	Maximum generation	200
Cross rate	0.8	F_{max} (ten thousands yuan)	7000
Mutation rate	0.1	μ	1
Reservation ratio of excellent chromosomes	10%	ρ	1

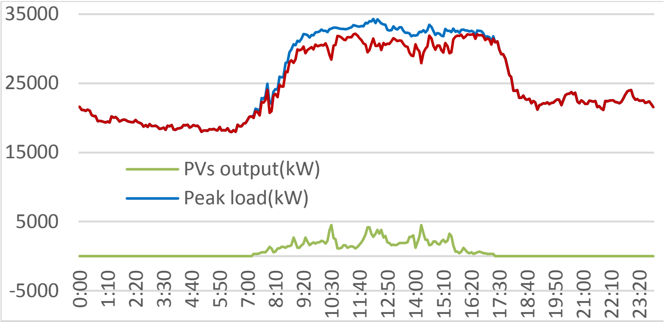

Fig. 9. The peak load curve and PVs output curve in the summer of 2021.

B. The planning schemes analysis

A five-years distribution network planning is developed by using reliability-based planning method, ADS planning method and HI-based planning method of distribution network. The treatment of three planning methods in the model and the number of decision variables and constraints are shown in Table 9 and Table 10 separately.

TABLE 9

TREATMENT OF THREE KINDS OF DISTRIBUTION NETWORK PLANNING MODELS

Planning methods	Consider equipment HI?	Using NNSs?	Chang of model
Reliability-based	No	No	Objective function doesn't include replacement cost of equipment and greenness risk cost.
ADS	No	Yes	Objective function doesn't include replacement cost of equipment
HI-based	Yes	Yes	No change

TABLE 10

THE NUMBER OF DECISION VARIABLES AND CONSTRAINTS IN DISTRIBUTION NETWORK PLANNING MODELS

Planning methods	The number of decision variables	The number of constraints
Reliability-based	7	166
ADS	20	178
HI-based	21	178

Three optimal distribution network planning schemes are obtained by INGA and STA. The evolutionary process of optimal solutions is shown in Figure 10. This figure shows that total risk cost of HI-based optimal distribution planning scheme is lowest, verifying the science and effectiveness of the proposed planning method. The risk analysis results of three distribution network planning schemes see Figure 11 and Table 11（see appendices）. The network structures of planning schemes are shown in Figure 12, in which green lines are new branches built for new load points and blue lines are built for solving overloading problem of cable 15. We can see that:

1) In the HI-based planning scheme, although the replacement cost of equipment increases compared with other schemes, but reliability risk is low. Meanwhile, the use of DR saves the expansion costs. So the total risk cost is minimum.

2) In the ADS planning scheme, although the expansion cost is reduced by DR, reliability risk is relatively high for no replacement of the aging equipment. So the total risk cost is not least.

3) In the reliability-based planning scheme, the overload problem of lines can be solved only by constructing a new feeder. The construction cost is higher than the other two schemes. In addition, reliability risk is relatively high for no replacement of the aging equipment. The total risk cost is the highest.

The scale of construction and reinforcement is shown in Table 12 (see appendices). The planning results show:

1) In the reliability-based planning scheme, it is necessary

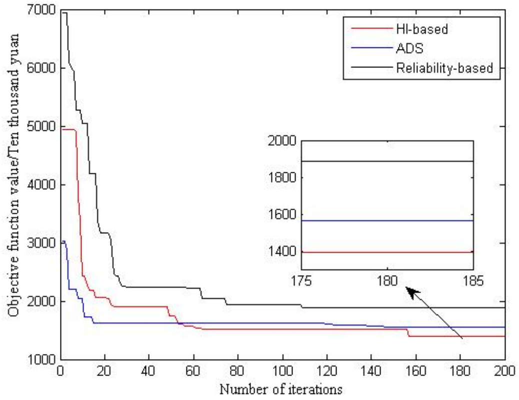

Fig. 10. The evolutionary process of optimal solutions using INGA.

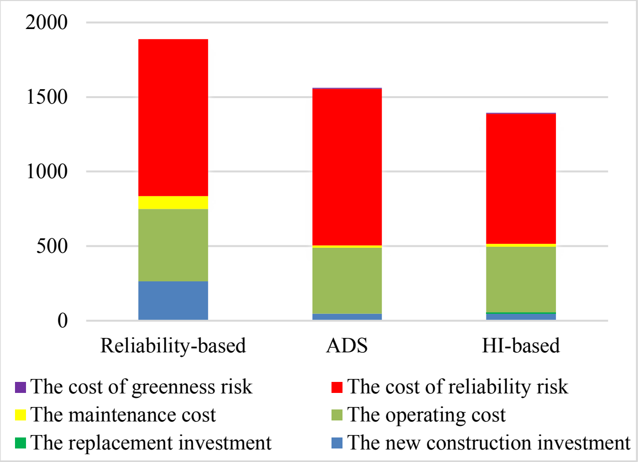

Fig. 11. Risk analysis of three kinds of distribution network planning schemes (Unit: ten thousand yuan)

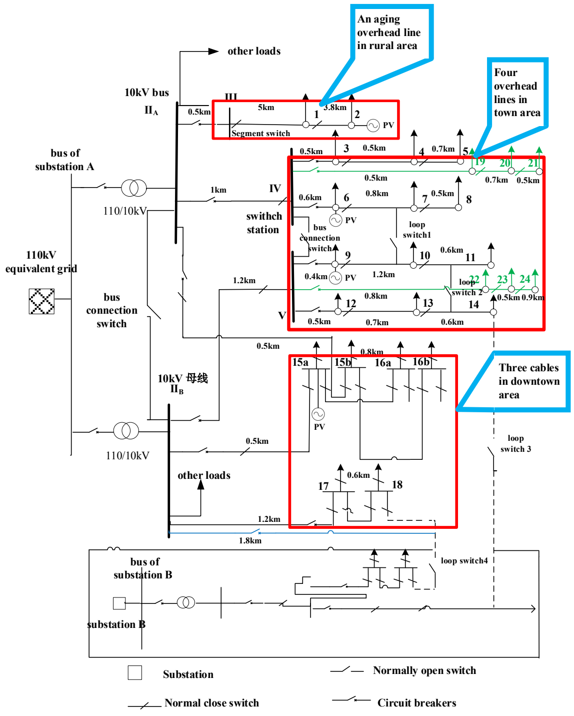

Fig. 12. The grid structure of distribution network planning scheme.

to establish a new feeder without considering NNSs. Because loading rate of line 25 (cable) in the planning network is about 71%. And the configuration is changed from the single ring to two suppliers and one spare. There are no lines to be replaced without considering the health conditions of equipment.

2) In the ADS planning scheme, DR (i.e. shedding load of node 18) is used to solve the overload problem of line 25. There is no need to build new feeders. There are no lines to be replaced without considering equipment HI.

3) In the HI-based planning scheme, DR (i.e. shedding load of node 18) is used to solve the overload problem of line 25. For the HI of overhead line 0 (II_A-III) degrades to 7.5 from 6.1 and POF increases from 12 times / (100 km·year) to 63 times/ (100 km·year) in 2021. Therefore, the line 0 is replaced in 2021.

C. The performance analysis of algorithms

1) Computational Efficiency and INGA Parameter Analysis:

The computational time for a 5-year EPADN study based on the proposed approach in this paper is about 5 minutes in MATLAB software on Intel CORE i5-4590 PC with clock speed 3.3 GHz and 8GB RAM. In order to show the stability of the proposed algorithm for EPADN, the algorithm is run for 50 times for HI-based planning and the mean and standard deviation (SD) of the total risk cost are obtained. Some results for the mean and SD of the total risk cost are presented in Table13. In order to keep the time of simulation, approximately, constant, the product of population and maximum iterations is maintained fixed in this analysis.

TABLE 13

THE RESULTS OF 50 RUN OF THE PROPOSED EPADN

Option	Population	Maximum iterations	Mean of R (ten thousand yuan)	SD of R (%)
1	60	200	1395	1.1
2	80	150	1421	2.0
3	100	120	1419	2.2
4	120	100	1474	2.4

As seen in Table 13, in options 1 and 2, the SD of option 1 is smaller than the SD of options 2. In addition, the mean value of option 1 is smallest in the five options. Therefore, for EPADN problem in this paper, the INGA parameters in option 1 are selected. The result for option 1 presents that the SD of the solution is about 1%, showing the proposed solution in this paper is a good and reliable solver for the EPADN.

2) Comparative analysis of different algorithms

In order to verify the applicability and performance of INGA, three different algorithms, i.e. SGA, INGA and particle swarm optimization (PSO) are used to solve EPADN model. The evolutionary process of three different algorithms is shown in Figure 13. The results show that：

(1) INGA's convergence accuracy is superior to SGA's and PSO's and SGA's convergence accuracy is better than PSO's. This indicates that INGA used to solve planning model built in the paper is with higher reliability of optimal solution and greater probability to get the optimum point of the objective function.

(2) Judging from the process of iteration convergence, the

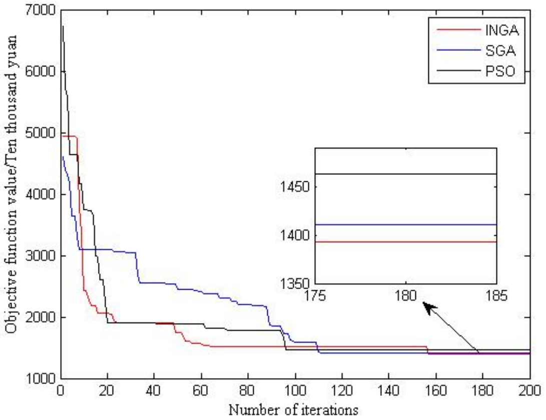

Fig. 13. The evolutionary process of three different algorithms.

optimum value of populations obtained by PSO after initialization is largest. But PSO converges quickly to near extreme value based on iterations and converges to the ultimate value of objective function after 96 iterations. This means PSO is with strong local searching ability, but lack of effective measures to jump from local optimal solution and easy to fall into local optimum.

(3) Compared with PSO, local searching ability of INGA and SGA is weak, but their global search ability is strong. Despite failing to quickly reach near the extreme point, the optimal solution of population obtained by SGA has been improved continuously, until it reaches the final convergence value.

(4) Compared with SGA, INGA falls into local optimum after 60 iterations. But in essence, INGA is with effective measures to jump from the local optimal solution and jumps from local optimum after 158 iterations. At last, INGA gets the optimal solutions with highest convergence accuracy.

VI. CONCLUSION

Domestic and foreign research shows that the application of HI theory and its extension to the field of risk control have become the trend of future distribution asset management and play a guiding and supporting role to further improve the level of distribution network planning and maintenance. Meanwhile power grid's stage of development in China also requires distribution planning to consider health status of equipment and network to obtain the optimal distribution planning scheme. This paper presents a new EPADN integrating HI and NNSs, which can solve some problems with minimum risk, such as the replacement strategy of equipment, the uncertainty of DERs output and the deficiency of traditional planning. It can reduce or delay investment cost and improve the power supply reliability and economic and social benefits. The main contributions are as follows:

1) In the non-capacity planning, the equipment replacement strategy is determined according to HI and risk level, and POF is estimated based on present and future HI to make power supply reliability evaluation more accurate.

2) In the capacity planning, a risk analysis method considering the uncertainty of load and renewable energy is proposed, which can cope with future load growth and non-normal operation conditions of distribution network by NSs and NNSs.

3) In order to improve the solution quality and efficiency, a method integrating INGA and STA is proposed to solve the EPADN. A combination of both can play the advantages of two kinds of algorithms.

4) The planning method is applied to actual 22-node distribution network in China and the applicability and effectiveness of the planning method and INGA proposed in the paper are proved. The results show that the total risk cost of EPADN is minimum, equipment replacement strategy based on HI and risk is more cost-effective and NNSs are more economical to cope with existing load growth and the uncertainty of DERs output. INGA whose convergence accuracy is superior to SGA's and PSO's is with strong global search ability and effective measures to jump from local optimal solution.

APPENDIX

Table 5-8 and Table 11-12 are shown as follows.

TABLE 5
HI AND RELIABILITY DATA OF 10KV LINES

Equipment	HI	POF(times / 100 km · year)	Average repair time (h)
Overhead lines	0.9	8.23	2.5
Overhead line 0(II$_A$—III)	6.1	11	2.5
Cable lines	1.5	3.24	5.5

TABLE 6
HI AND RELIABILITY DATA OF OTHER EQUIPMENT

Equipment	HI	POF (times / 100 km · year)	Average repair time(h)	Switching time(min)
10kV circuit breaker	0.7	0.10	7.5	1
10kV switch(section and loop)	1.1	1.24	4	1
110kV transformer	0.8	0.5	24	——

TABLE 7
THE COMPREHENSIVE COST OF 10KV LINES

Type	Property	Size	Cost (ten thousand yuan / km)
10kV overhead lines	Lead line	LGJ-300	29.4
	Trunk line	LGJ-185	15.5
	Branch 1	LGJ-120	11.4
	Branch 2	LGJ-95	10.08
10kV cables	Trunk line	YJV22 XLPE-3×300	120

TABLE 8
THE RELEVANT PARAMETERS IN PLANNING MODEL

Parameter	Value	Unit	Parameter
C_p	0.5	yuan	C_p
λ	2%	-	λ
d_S	60	yuan/kWh	d_S
U_{DSR_n}	Resident price: 0.5 Commercial price: 0.64	yuan/kWh	U_{DSR_n}
U_{DG_pn}	1.09(PV price)	yuan/kWh	U_{DG_pn}
U_{DG_qn}	1.09(PV price)	yuan/kvarh	U_{DG_qn}

maximum load duration	2	hours	maximum load duration
maximum load equivalent hour	3000	hours	maximum load equivalent hour

TABLE 11

RISK ANALYSIS OF THREE KINDS OF DISTRIBUTION NETWORK PLANNING SCHEMES (UNIT: TEN THOUSAND YUAN)

Schemes	Reliability-based	ADS	HI-based
New construction investment	263.94	47.94	47.94
Replacement investment	0	0	7.75
Operating cost	484.79	440.72	440.72
Maintenance cost	86.17	15.65	18.18
EENS loss	1053.32	1051.16	872.72
The cost of NNSs	0	5.71	5.71
Total	1888.22	1561.18	1393.02

TABLE 12

THE CONSTRUCTION AND REINFORCEMENT SCALE FOR THE THREE KINDS OF DISTRIBUTION NETWORK PLANNING SCHEMES

Planning method	New lines				Replacement of equipment				NNSs
	Lines	Type	Property	Length(km)	Lines	Type	Property	Length(km)	
HI-based	IV-19	Overhead	Trunk /185mm^2	0.5	Line 0(IIA—III)	Overhead	Trunk /185mm2	0.5	DR： shed all the load of node 18
	19-20	Overhead	Branch 1/120 mm^2	0.7					
	20-21	Overhead	Branch 2/95 mm^2	0.5					
	V-22	Overhead	Trunk /185mm^2	0.8					
	22-23	Overhead	Branch 1/120 mm^2	0.5					
ADS	The same with HI-based				None				The same with HI-based
Reliability-based	The same with HI-based				None				None
	IIB-18	Cable	Trunk / YJV22 XLPE-3×300	1.8					

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