# Planning distribution network using the multi-agent game and distribution system operators

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When planning the distribution network, the income of each market entity is calculated by a fixed price. How to take the price of power into account while developing the planning strategy for each organization in the actual power market is an urgent issue that needs to be addressed imminently. To address this problem, considering the continuous change in the market price due to the change in the supply–demand relationship in the actual power market, this article proposes a distribution network planning method which considers the distribution system operator (DSO) and multi-agent game. First, the planning decision model of distribution network companies and power users with different interest subjects is constructed with grid planning and DG operation as decision variables. Second, DSO is introduced to the game framework. Based on the distribution locational marginal pricing (DLMP), a price accounting model is being developed. Then, the transfer relationships and game behavior among the distribution company, power users, and DSO are analyzed. Finally, an iterative search algorithm is used to solve a multi-agent game planning model of a distribution network that takes into account price signals in the power market. Examples based on IEEE 33-bus systems validate the suggested method's validity and efficacy.

KEYWORDS

distribution network planning, DSO, DLMP, multi-agent game, iterative search algorithm

## 1 Introduction

As China's energy market reform continues to advance, the distribution side market has gradually been opened to social capital (Liu et al., 2018; Yang et al., 2022a; Wang et al., 2023). The highly open electricity market environment makes the types and quantity of investment and operation subjects in the supply and demand side increase continuously (Chen et al., 2019a; Yang et al., 2021). With the intention of maximizing their own interests, they independently take part in the planning and management of the distribution network. As a result, the traditional planning method based on holistic rationality is difficult to apply to distribution network planning in the current electricity market environment because it cannot accurately describe the ubiquitous competitive relationship in the electricity market. In this regard, based on individual rationality, the development of distribution network planning methods that fully consider market competition and game mechanisms has important theoretical and practical significance (Lu et al., 2014; Yu et al., 2022).

At present, many literature reports have proposed distribution network planning methods, considering the market-oriented game (Li et al., 2013; Liao et al., 2013; Zeng et al., 2017; Yang et al., 2019). In Li et al. (2013), for the first time in distribution network planning, the game

between investment cost, line loss, and voltage quality is examined to determine the ideal location and size of distributed generations. Zeng et al. (2017) analyzed the interaction between the distribution company and the DG investor, and proposed a two-level Stackelberg game model, in which the distribution company acts as the game leader to expand the network and the DG investor acts as the game follower to locate and size the DG. Liao et al. (2013) studied the game relationship between the substation investor and the distribution network company so that the substation investor can select the appropriate standby feeder according to the network structure planned by the distribution network company, thereby improving the reliability of the distribution network. By introducing virtual players, for the purpose of the collaborative design of a distribution network under uncertainty and a multi-agent game, Yang et al. (2019) integrated robust optimization with game theory. However, all of the aforementioned references apply fixed prices to determine the income in order to carry out the distribution network design. The real power grid's power pricing will fluctuate when the relationship between power supply and demand changes, which directly affects the power load of users and the planning and decision-making of the distribution network. It is clear that the standard distribution network planning technique, which takes market-oriented games into account, overlooks the influence of time-of-use/tiered energy prices on planning decision-making. As a result, it is challenging to create an accurate and appropriate planning scheme.

Currently, there are some research studies that apply locational marginal pricing (LMP) to distribution network planning. Chen et al. (2019b) introduced the carbon trading mechanism, analyzed the bilateral bidding relationship between power generation companies and power users, and constructed a market clearing model based on LMP. Taking into account the market trading system and relevant incentive policies for the development of wind power generation, Lou et al. (2019) described the construction of a bi-level model for the expansion planning of power generating investment in oligopolistic electricity markets that includes wind power generation, with power generation companies and power trading centers as the decision-making bodies. Taking into account DG's contribution to the distribution system's efforts to save energy and reduce emissions, Wang et al. (2018) proposed a nodal pricing method of the distribution network, taking into account the task allocation of gas emission reduction of the distribution network and the game behavior of the main market by using the concept of the cooperative game. Hu et al. (2019) constructed a distribution network day ahead the optimal dispatching model based on distribution locational marginal pricing (DLMP), in which a distributed iterative solution is achieved by the interaction of "price–power" information between the distribution system operator (DSO) and load aggregator (LA) (Li et al., 2018). The planning methods involved in the aforementioned literature are all based on LMP analysis of game relationships between different players and construct the corresponding model, but the following problems are observed.

The previous references either do not consider the game relationship between DSO and other market players, or only considers the interaction and information exchanges with a part of the market participants and DSO, while the information on other market participants remains unchanged. In the actual electricity market planning, various game relationships will have an impact on the electricity price and then affect the planning decision. For example, with the integration of DG into the distribution network (Liao et al., 2018), the selection of its access location

and line transmission capacity may also affect the decision-making of other market players and DSO (Li et al., 2023), and then affect the nodal marginal price of the distribution network (Gao et al., 2020). If we cannot fully consider the game relationship between DSO and other subjects in the market, it will be difficult to obtain an accurate planning scheme (Chen et al., 2021).

In view of this, a distribution network planning method considering distribution system operators and the multi-agent game is proposed in this paper. First, the planning decision model of distribution network companies and power users with different interest subjects is constructed with grid planning and DG operation as decision variables. Second, DSO is introduced as a special market entity, and the electricity price accounting model is established based on DLMP theory. Then, based on the planning and operation mechanism of the distribution market, the transitive relationship and game behavior among distribution network companies, power users, and distribution system operators are analyzed, and a multi-agent game planning model considering the market price is established, which is finally solved using an iterative search algorithm. Compared with the traditional distribution network planning method that considers the market game, the method not only considers the position and the capacity of the DG but also considers the influence of the capacity expansion of a newly built line on the node marginal price so that the calculation accuracy of the node marginal price of the distribution network is high. On this basis, by examining the transmission relationship and game behavior among distribution network companies, power customers, and distribution system operators, the planning scheme's accuracy is increased. The accuracy and efficiency of the suggested solution are confirmed by an example based on the IEEE 33-bus distribution system.

# 2 Planning decision model of each market's main body

In the market environment considered in this paper, the main bodies of investment planning are distribution network companies, power users, and distribution system operators. This particular topic of DSO is principally in charge of maintaining the distribution network's safety and accounting for energy pricing. Direct participants in distribution planning include electricity users and distribution network businesses. For distribution network companies, they reduce electricity prices through grid construction, thereby increasing electricity sales and revenue so as to maximize their own interests (Xu B. et al., 2023). For power users, it is hoped that the new distributed generation will be built to reduce the comprehensive expenditure on power consumption through the way of "self-generation and self-use, surplus access to the grid" (Nan et al., 2018). Different market entities belong to different interest groups (Nan et al., 2023), have various goals while engaging in planning, and come to conclusion on their own. Therefore, it is important to build the relevant planned income models for the three market themes mentioned previously.

## 2.1 Power user planning model

Power users take part in the design and development of the distribution network by building new DG and consume electrical

energy in the mode of "self-generation and self-use, surplus access to the grid" (Li, 2017; Liu et al., 2020; Zhou et al., 2022). When the generated energy of the constructed DG is less than the load of the user node, the electric energy consumed by the user is transmitted by the main network through the distribution network, wherein the grid firm receives the grid crossing charge, and the node marginal price of the distribution network node serves as the means for settling electrical energy (Shen and Raksincharoensak, 2021). When the power generation of the constructed DG is more than the load of the user node, in addition to supplying its own load, the distribution network company will buy the extra power (Veeramsetty, 2021).

### 2.1.1 Objective function

The planning objective of power consumers is to lower the cost of their own electricity use (Zhang et al., 2023), and the distributed generation construction plan is the decision variable. The primary components of the goal function are DG power purchase costs, DG investment costs, DG maintenance and operation costs, and power sales revenue, and the specific calculation formula is shown in Eq.1.

$$U^{Use}(x_i, N_i) = C_B^{Use} + C_I^{Use} + C_O^{Use} - C_S^{Use}, \tag{1}$$

where $U^{Use}$ is the total expenditure of power users, $C_B^{Use}$ is the cost of acquiring energy for power users, $C_I^{Use}$ is the investment cost of the DG unit, $C_O^{Use}$ is the operation and maintenance cost of the DG unit, and $C_S^{Use}$ is the electricity sales income of the remaining generation of DG.

Therefore,

$$C_I^{Use} = \left( \theta_I \cdot \sum_{i=1}^{\Omega_i} x_i \cdot P_I^{DG} \cdot N_i \right) \cdot \frac{r(1+r)^{LT}}{(1+r)^{LT} - 1}, \tag{2}$$

$$C_O^{Use} = \sum_{t=1}^{\Omega_t} \theta_O \cdot P_I^{DG} \cdot T_t, \tag{3}$$

$$C_S^{Use} = \begin{cases} \sum_{t=1}^{\Omega_t} \sum_{i=1}^{\Omega_i} \theta_S \cdot \left( P^{DG} - P_t^D \right) \cdot T_t, P_t^{DG} > P_t^D \\ 0, P_t^{DG} > P_t^D, \end{cases} \tag{4}$$

$$C_B^{Use} = \begin{cases} \theta_B \cdot \sum_{t=1}^{\Omega_t} \left( \sum_{i=1}^{\Omega_i} \left( P_t^D - P_t^{DG} \right) + \sum_{d=1}^{\Omega_{-d}} P_t^D \right) \cdot T_t, \quad P_t^{DG} < P_t^D \\ \sum_{t=1}^{\Omega_t} \sum_{d=1}^{\Omega_{-d}} \theta_B \cdot P_t^D \cdot T_t, P_t^{DG} \geq P_t^D, \end{cases} \tag{5}$$

where $P_I^{DG}$ represents the DG unit's rated capacity, $P_t^{DG}$ is the generation at time $t$, and $P_t^D$ is the load at that same moment. $x_i = 0$ denotes that the selected $i$-th is disconnected from the DG, whereas $x_i = 1$ denotes that the selected $i$-th is connected to the DG; $\Omega_i$ is the newly formed DG group's node set that is connected to DG; $N_i$ represents the amount of brand-new DG units for the node $i$; $\Omega_t$ stands for the set of time $t$; $\Omega_d$ represents the set of load points; $\Omega_{-d}$ is the remaining load node set after eliminating the newly built DG node; $\theta_S$ is the grid electricity price for excess DG generation; $\theta_B$ represents the node's purchasing price. $r$ stands for the discount rate, and $LT$ indicates the device's life span.

### 2.1.2 Constraints

The main elements of the power user planning model's constraints are the restrictions on the number of DG nodes that may be selected and DG penetration constraints (Zhang and Luo, 2018; Li et al., 2021a).

(a) The limit on the number of DG nodes that can be chosen is as follows:

$$N_{i.\min} \leq N_i \leq N_{i.\max}, \tag{6}$$

where $N_{i.\min}$ and $N_{i.\max}$ are the minimum and maximum number of DGs that can be linked to the node $i$ that is being chosen, respectively.

(b) The restriction on DG permeability is

$$\sum_{i=1}^{\Omega_i} x_i \cdot P_I^{DG} \cdot N_i \leq \delta \cdot P_{load}. \tag{7}$$

## 2.2 Planning model of the distribution network company

### 2.2.1 Objective function

In order to optimize one's own revenue, the distribution network corporation primarily designs its distribution network in the power system planning process (Xu P. et al., 2023). The decision variable is the expansion plan of new lines (Yang et al., 2022b). The goal function accounts for the power sales income, the investment cost of additional extension lines, the price of purchasing electricity from the main network, and the cost of acquiring electricity from DG.

$$C^{DN}(y_j) = C_S^{DN} - \left( C_I^{DN} + C_{B1}^{DN} + C_{B2}^{DN} \right), \tag{8}$$

where $C^{DN}$ represents the distribution network company's overall revenue, $C_S^{DN}$ represents the distribution network company income of selling electricity, $C_I^{DN}$ is the investment cost for new line expansion, $C_{B1}^{DN}$ represents the cost of purchasing power for the primary network, and $C_{B2}^{DN}$ represents the cost of purchasing DG from end users.

Therefore,

$$C_I^{DN} = \left( \psi_I \cdot \sum_{j=1}^{\Omega_j} y_j \cdot l_j \right) \cdot \frac{r(1+r)^T}{(1+r)^T - 1}, \tag{9}$$

$$C_S^{DN} = C_B^{Use}, \tag{10}$$

$$C_{B2}^{DN} = C_S^{Use}, \tag{11}$$

$$C_{B1}^{DN} = \psi_B \cdot \sum_{t=1}^{\Omega_t} \left( \sum_{d=1}^{\Omega_d} P_t^D - \sum_{i=1}^{\Omega_i} P_t^{DG} + PLoss_t \right) \cdot T_t, \tag{12}$$

where $y_j$ is a variable from 0 to 1, $y_j = 0$ denotes that the $j$-th line to be freshly created is not picked, and $y_j = 1$ denotes that the j-th line to be freshly created is picked. $l_j$ indicates the length of the $j$-th line that will be expanded; the new line's unit length cost is indicated by $\psi_I$; $\psi_B$ indicates the cost per unit of electricity obtained from the more advanced power grid; $\Omega_j$ represents a group of lines that need to be expanded; and $PLoss_t$ represents the system network loss at time $t$.

### 2.2.2 Constraints

Constraints on line selection, branch power flow, and security are the essential requirements in the distribution network company planning model.

(a) The line selection constraint is

$$0 \leq y_j \leq 1. \tag{13}$$

(b) The branch power flow constraint is

$$
\begin{cases}
P_{i,t} = U_{i,t} \cdot \sum_{j \in i} U_{j,t} \cdot \left( G_{ij} \cdot \cos \theta_{ij} + B_{ij} \cdot \sin \theta_{ij} \right), \\
Q_{i,t} = U_{i,t} \cdot \sum_{j \in i} U_{j,t} \cdot \left( G_{ij} \cdot \sin \theta_{ij} - B_{ij} \cdot \cos \theta_{ij} \right),
\end{cases} \tag{14}
$$

where $P_{i,t}$ and $Q_{i,t}$ stand for the node $i$'s active power and reactive power at time $t$, respectively; $U_{i,t}$ and $U_{j,t}$ represent the voltage amplitudes of node $i$ and node $j$ at time $t$, respectively; $G_{ij}$ and $B_{ij}$ represent the conductance and susceptance of the branch $ij$, respectively; and $\theta_{ij}$ represents the phase angle difference between the voltages at nodes $i$ and $j$.

(c) Safety constraints are

$$
\begin{cases}
U_{i.\min} \leq U_{i,t} \leq U_{i.\max}, \\
P_{ij,t} \leq P_{ij.\max},
\end{cases} \tag{15}
$$

where $U_{i.\min}$ and $U_{i.\max}$ represent the lower limit and the higher limit of the voltage amplitude of the node $i$, respectively; $P_{ij,t}$ and $P_{ij.\max}$ represent the transmission power of the branch $ij$ and its upper limit value, respectively.

## 2.3 Distribution system operator's operation model

### 2.3.1 Objective function

DSO stimulates electricity consumption by altering the distribution network's nodal marginal prices (Zhu et al., 2023), which alters the demand for purchasing and selling electricity, and manages the distribution network's operational health. The minimum total cost of purchasing electricity can be taken as the optimization objective of DSO (Dewey and DongLi, 2020), and the following is its objective function:

$$
\min f \left( P_t^{UG}, P_{t,i}^{DG} \right) = \sum_{t=1}^{\Omega_t} \left( \psi_B \cdot P_t^{UG} + \theta_S \cdot \sum_{i=i}^{\Omega_i} \left( P_{t,i}^{DG} - P_t^{D} \right) \right) \cdot T_t, \tag{16}
$$

where $f(\bullet)$ represents the total cost function, $P_t^{UG}$ represents the quantity of energy obtained from the upper-level power grid at time $t$, and $P_{t,d}^{DG}$ represents the amount of DG power purchased from the user at time $t$.

### 2.3.2 Constraints

$$
\begin{cases}
P_{gi} - P_{di} - U_i \sum_{j=1}^{N} U_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) = 0, \\[2mm]
Q_{gi} - Q_{di} - U_i \sum_{j=1}^{N} U_j \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) = 0, \\[2mm]
P_{t,i.\min}^{DG} \leq P_{t,i}^{DG} \leq P_{t,i.\max}^{DG}, \quad i \in \Omega_i, \\
Q_{t,i.\min}^{DG} \leq Q_{t,i}^{DG} \leq Q_{t,i.\max}^{DG}, \quad i \in \Omega_i, \\
U_{t,i.\min} \leq U_{t,i} \leq U_{t,i.\max}, \quad i \in N, \\
P_{t,l.\min} \leq P_{t,l} \leq P_{t,l.\max}, \quad i \in N_l,
\end{cases} \tag{17}
$$

where $P_{gi}$ and $Q_{gi}$ represent the generator's active and reactive power at node $i$, respectively; $P_{di}$ and $Q_{di}$ represent active and reactive loads of the node $i$, respectively; voltage amplitudes at nodes $i$ and $j$ are represented by letters $U_i$ and $U_j$, respectively; the highest and lower limit limitations to the DG generator unit $i$'s active power output at time $t$ are $P_{t,i.\max}^{DG}$ and $P_{t,i.\min}^{DG}$, respectively; $Q_{t,i.\max}^{DG}$ and $Q_{t,i.\min}^{DG}$ are the upper and lower limit constraints of the reactive power output of the DG generator unit $i$ at time $t$, respectively; the voltage amplitude of the node $i$ at time $t$ is constrained by $U_{t,i.\max}$ and $U_{t,i.\min}$, which are respectively its highest and lower limits; $P_{t,l}$ represents the active power flowing through line $l$ at time $t$; $P_{t,l.\max}$ and $P_{t,l.\min}$ are the highest and lower limit restrictions, respectively, on the active power allowed to flow through line 1 at time $t$; N represents the total node count; and $N_l$ represents the total line count.

### 2.3.3 Network's nodal marginal price of distribution

The Lagrangian equation is used to calculate the nodal marginal price of the distribution network (Yuan et al., 2016). Combined with the objective function and constraints of the DSO operation model (Ma et al., 2021), the following is how the Lagrangian function model of the distribution network's nodal marginal price is built:

$$
L = f \left( P_t^{UG}, P_{t,i}^{DG} \right) - \sum_{i=1}^{n} h(x) - \sum_{i=1}^{r} g(x), \tag{18}
$$

where $h(x)$ is the equality constraint in Eq. 17, and $g(x)$ is the inequality constraint; and $n$ and $r$ are the number of equality and inequality constraints in Eq. 17, respectively.

The inequality constraints are transformed into equality constraints as follows:

$$
\begin{aligned}
g(x) + u &= g_{\max}, \\
g(x) + o &= g_{\min},
\end{aligned} \tag{19}
$$

where $g_{\max}$ and $g_{\min}$ are the upper and lower limits of the inequality constraint, respectively; $o$ and $u$ are the introduced slack variables, respectively.

In order to optimize the independent variable within the feasible region, the barrier function is introduced into the original Lagrangian function as follows:

$$
\begin{aligned}
L(P_g, \lambda, \beta, w, u, o) = {} & F(P_g) - \mu \sum_{i=1}^{n} (\ln o_i + \ln u_i) - \lambda^T h(x) \\
& + w^T (g(x) + u - g(x)_{\max}) \\
& - \beta^T (g(x) - o - g(x)_{\min}),
\end{aligned} \tag{20}
$$

where $\lambda$, $w$, and $\beta$ are Lagrange multiplier vectors after the equality constraint in Eq. 17, and the inequality constraint in Eq. 19 is converted into the equality constraint; Therefore, $\lambda$ is a column vector of $n \times 1$; $w$ and $\beta$ is a column vector of $r \times 1$; $\ln o$ and $\ln u$ are the introduced barrier functions; and $\mu$ is the barrier parameter.

The nodal marginal price of the distribution network is as follows:

$$
DLMP_i = \frac{\partial L}{\partial P_i} = \lambda_i, \tag{21}
$$

where $DLMP_i$ represents the distribution network nodal marginal price of the node $i$.

**FIGURE 1**
Transmission relationship diagram of each subject.
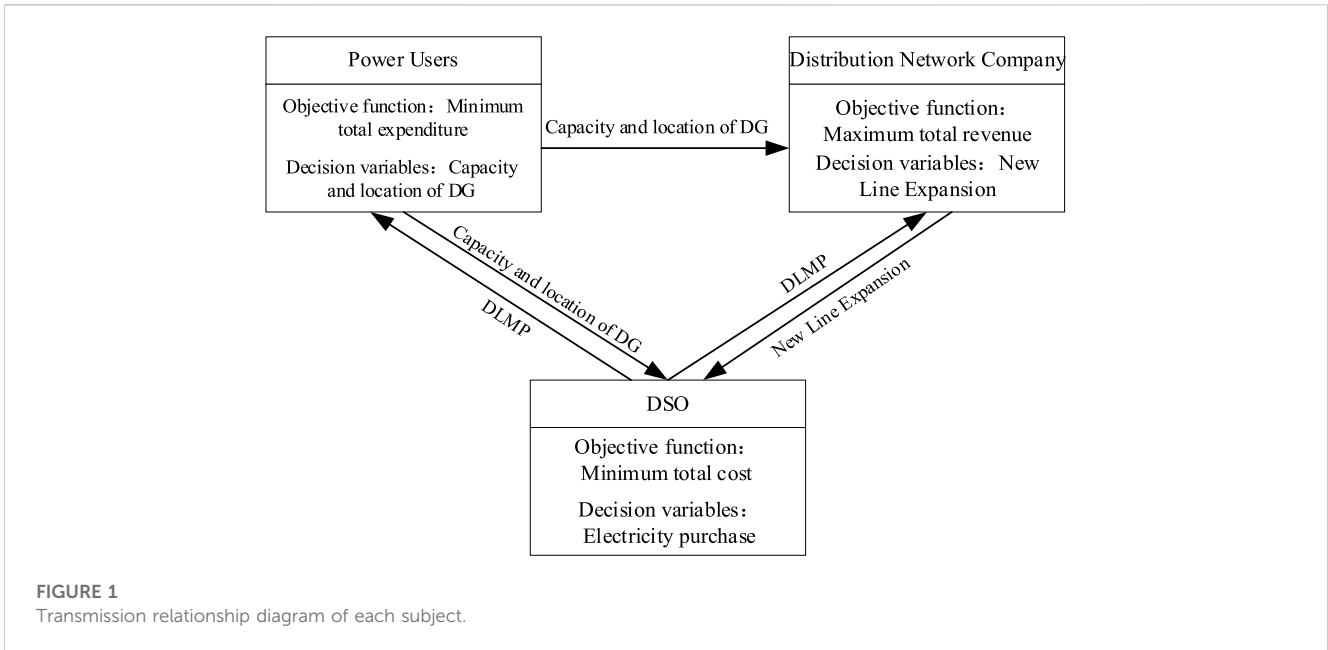
# 3 Considering the the planning game framework of each agent of the distribution system operator

## 3.1 Analysis of the transfer relationship

Distribution network planning considering DSO in this paper involves power users, distribution network companies, and special subject DSO, and Figure 1 illustrates the transmission relationship diagram of each subject.

In accordance with the DSO's computed distribution network node marginal price, a power user chooses the site and establishes the DG's capacity, determines the amount of electricity purchased from a distribution network company, and transmits the location, capacity, and electricity purchase information on DG to the distribution network company and the DSO. According to the location, capacity, and power purchase information on DG and the node marginal price calculated by DSO, the distribution network company builds and expands the current grid structure and transmits it to DSO. According to the distribution network company's new line expansion plan, DSO determines the new node marginal price and passes it to the power users; power users decide the new DG location and capacity according to the new price information so as to calculate the total cost expenditure and enter a new round of game.

## 3.2 Game behavior analysis

On the basis of independent decision-making, power consumers and distribution network companies must collaborate to finish the planning and construction of the power system (Fang et al., 2022; Li et al., 2022), and the planning strategies of power users and distribution network businesses must be mastered by the market operation of DSO.

The three actions in the game have a sequence, and the dynamic game behavior diagram is shown in Figure 2.

According to the node marginal price of the distribution network estimated by the previous round of DSO in the game round depicted in Figure 2, by changing the location and capacity scheme and power purchase plan of DG, the power user reduces its own energy costs. The power user then transmits the location and capacity scheme and power purchase plan of DG to the distribution network company and the special subject DSO; DSO calculates the new nodal marginal price of the distribution network according to the DG location and capacity scheme and the power purchase plan of power users, and transmits it to the distribution network company. The distribution network company updates the new line expansion plan before sending it to the special main body DSO in order to maximize the overall advantage of the distribution network, according to the energy pricing information supplied by DSO. DSO estimates the marginal price of the new node and transmits it to the power customers in accordance with the growth plan of the new line of the distribution network company. Power users then adjust the location and capacity scheme, and the power purchase plan of DG once more, and play the next round of the game based on the new electricity price information.

In the game process, when neither the power user nor the distribution network company can obtain more benefits by changing the strategy (Zhang et al., 2022) and when the game reaches equilibrium, it takes the following form:

$$\begin{cases} S_{Use}^* = \mathrm{argmax} C^{Use}(S_{Use}, S_{DN}^*, DLMP^*), \\ S_{DN}^* = \mathrm{argmax} C^{DN}(S_{Use}^*, S_{DN}, DLMP^*), \end{cases} \quad (22)$$

where $S_{Use}^*$ and $S_{DN}^*$ are the optimal strategies for the power users and the distribution network companies to reach the equilibrium state, respectively; $DLMP^*$ represents the optimal marginal price of the node.

**FIGURE 2**
Dynamic game behavior diagram.
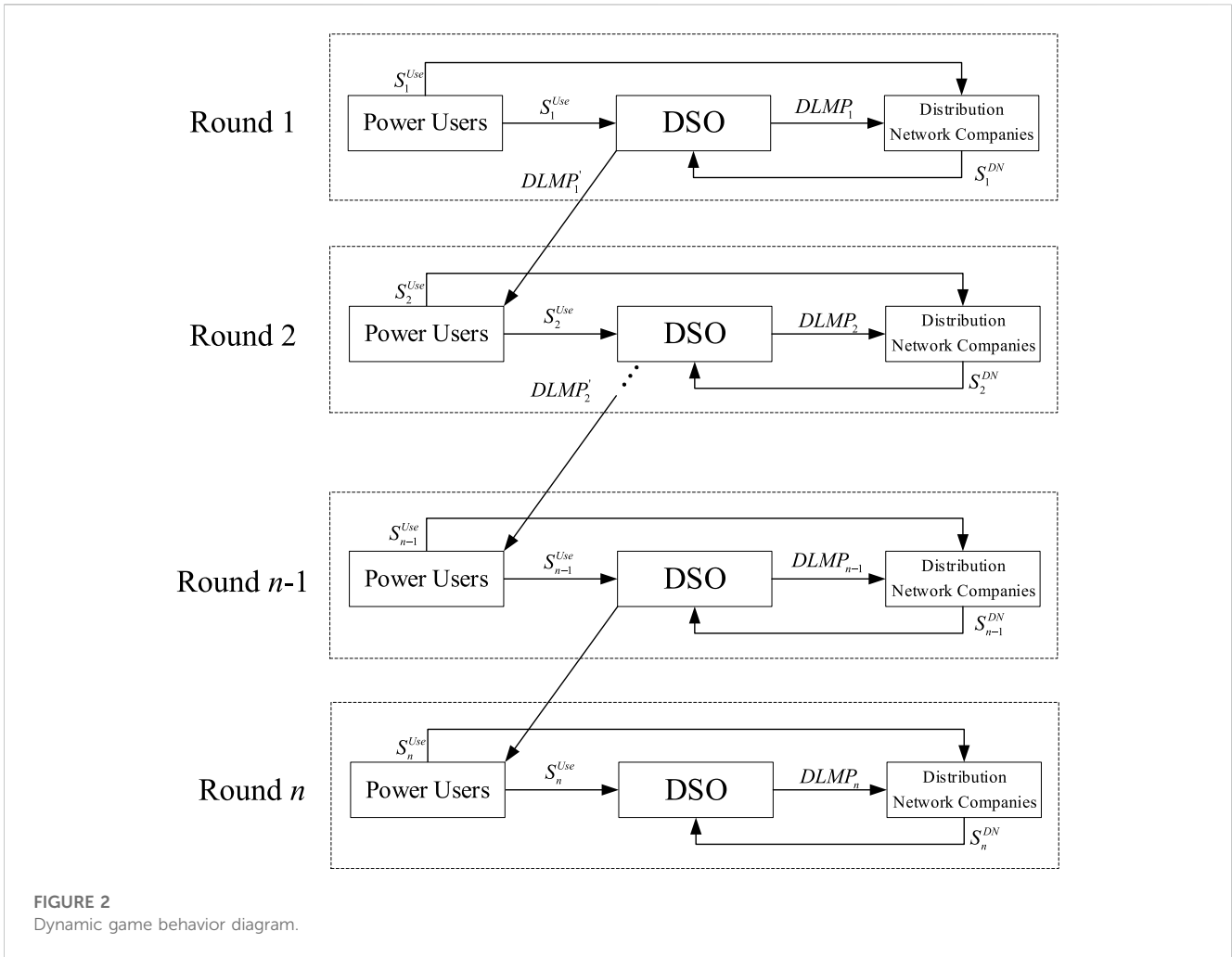
# 4 Model solving

The Nash equilibrium for the proposed model is solved using an iterative search technique (Yang et al., 2011).

The following are the stages to obtain the solution.

**Step 1:** Enter raw parameters and data. Enter the data required for the game model and the parameters necessary to calculate the payoffs of the players.

**Step 2:** Generate a set of game player strategies. A self-strategy set $\{S_1^{Use}, S_2^{Use}, \dots S_n^{Use}\}$ is generated by power users according to a node that is to be selected of a newly built DG unit; the distribution network company generates a strategy set $\{S_1^{DN}, S_2^{DN}, \dots S_m^{DN}\}$ according to the set that is to be selected of the newly built expansion line.

**Step 3:** Initialize the planning strategy scheme (Fu et al., 2023). Power users and distribution network companies choose a group of planning strategy schemes at random from their respective strategy sets to serve as the initial value of the planning schemes, and DSO determines the first price using the power users' and distribution network companies' planning schemes.

**Step 4:** Set the iteration's starting value $k = 2$.

**Step 5:** Participants perform scenario optimization (Liu et al., 2016). In the $k$-th iteration process, the distribution network company and DSO were informed of the location and capacity scheme of DG by the power user in accordance with the power user's minimal power consumption cost; the distribution network company maximizes its own interests to determine the expansion scheme of new lines and transmits it to power users and DSO. DSO calculates the new electricity price information according to the location and capacity scheme of power users and the expansion scheme of new lines of the distribution network company, and transmits it to power users and the distribution network company. The primal-dual interior point technique is used to calculate the pricing information for DSO (Wei et al., 1998).

**Step 6:** Determine if the equilibrium state has been attained. If two successive game rounds' planning plans are identical, the game finds equilibrium, and step 7 is carried out; if not, set $k = k+1$ and return to step 5.

**Step 7:** Output the equilibrium solution $(S_{Use}^*, S_{DN}^*)$ of the model and the final benefits of each party (Yang et al., 2022c).
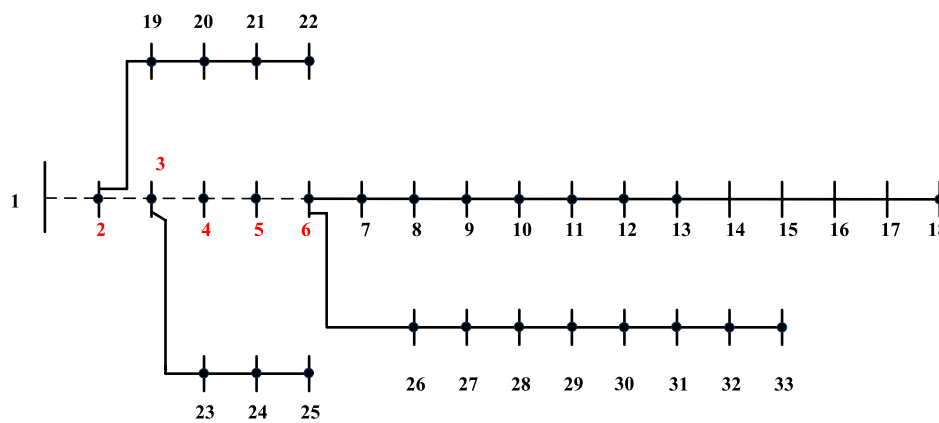
**FIGURE 3**
IEEE 33-bus system.

TABLE 1 Related parameters of the DG unit.

| Capacity of the single unit (kW) | Unit investment cost (¥/kW) | Unit operation and maintenance cost (¥/kW • H) |
|---|---|---|
| 50 | $1.5 \times 10^4$ | 0.2 |

TABLE 2 Related parameters of the DG unit.

| Unit cost (¥/km) | Impedance (Ω/km) | Maximum current/A | Life cycle/year |
|---|---|---|---|
| $6 \times 10^6$ | $0.27 + j0.4$ | 380 | 20 |

# 5 Example analysis

## 5.1 Parameter setting

In this study, the simulation analysis is applied to the IEEE 33-bus distribution network system (Li et al., 2021b), and Figure 3 shows its topology. The dotted line represents the new expansion line to be selected, and the red node represents the node to be chosen for the power user to install DG.

Table 1 displays the relevant DG unit specifications. The power consumers can choose from the following DG nodes: {2, 3, 4, 5, and 6}. The DG unit's output upper and lower limits are set at 0.9 and 0.7 of the rated capacity, respectively.

The related parameters of the DG unit are shown in Table 1, and all of the DG nodes to be selected installed by power users are {2, 3, 4, 5, and 6}. The DG unit's output upper and lower limitations are set at 0.9 and 0.7 of the unit's rated capacity, respectively.

The new expansion line set of the distribution network company is {1–2, 2–3, 3–4, 4–5, and 5–6}, and Table 2 displays the pertinent DG unit parameters. The distribution network company pays 0.4 ¥/kW•H per unit for the electricity it buys from the superior power grid.

Calculating the primary planning schemes in this paper allows for the effectiveness of the suggested strategy to be confirmed, various benefits and total benefits in the following three methods, and contrasting the outcomes of Method 3 with those of Methods 1 and 2.

Method 1: A distribution network planning method that does not consider DSO but considers the game relationship of each agent, that is to say, the cost of electricity is set at 0.75 ¥/kW•H, and power customers purchase it from the distribution network company at a single price.

Method 2: The distribution network planning method considering DSO but not considering the game relationship of each main body, that is, the distribution network planning strategy is based on the organization that operates the distribution network and the power users' best overall planning decision.

Method 3: A technique for constructing distribution networks that takes each agent's game relationship and DSO into account. In the method proposed in this research, power users buy energy from the distribution network firm using the nodal marginal price of the distribution network. The nodal marginal price of the distribution network is initially fixed at 0.75 ¥/kW•H throughout the iteration process.

## 5.2 Planning results and analysis

### 5.2.1 Planning results and analysis

The planning schemes of power users and distribution network companies obtained by using the three methods are shown in Table 3, and the price information on DG nodes to be selected obtained using Methods 2 and 3 is shown in Table 4.

TABLE 3 Planning schemes.

| Subject | Planning scheme | | |
|---|---|---|---|
| | Method 1 | Method 2 | Method 3 |
| **Power users** | 2(0),3(0),4(0) 5(150),6(150) | 2(100),3(100),4(50) 5(50),6(0) | 2(100),3(100),4(50) 5(0),6(0) |
| **Distribution network company** | 1–2(1),2–3(1) 3–4(1),4–5(0),5–6(0) | 1–2(0),2–3(0) 3–4(0),4–5(0),5–6(1) | 1–2(0),2–3(0) 3–4(0),4–5(1),5–6(1) |

TABLE 4 Price information on the DG node to be selected.

| Node | | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Price (¥/kW•H)** | **Method 2** | 0.7536 | 0.7550 | 0.7525 | 0.7511 | 0.7203 |
| | **Method 3** | 0.7527 | 0.7537 | 0.7505 | 0.7391 | 0.7233 |

Tables 3, 4 demonstrate the planning results obtained by the three methods are not the same, and the nodal marginal prices of DG nodes to be selected obtained by methods 2 and 3 are also different. The reason is that, despite the fact that Method 1 takes into account each subject's game relationship while planning in a market setting, its planning scheme is generated through a continuous game under the assumption of fixed pricing and ignores the impact of dynamic changes in the whole market price on the planning scheme. Although Method 2 considers the change in the market price, it is predicated on maximizing the interests of distribution network firms and power consumers as a whole at the expense of certain other subjects' interests, ignoring the game relationship of planning strategies among the subjects. Method 3 not only considers the market price signal but also considers the game relationship between the subjects so that each market subject can consider the market price to the maximum extent in the process of a continuous game and constantly adjust its own scheme through the guiding role of the market price in order to achieve the best planned decision scheme, given the pricing. Therefore, the planning schemes obtained by the three methods are not the same, and the nodal marginal prices of the nodes to be selected by the DG are also different.

## 5.2.2 Comparative analysis
(a) Necessity analysis of considering DSO in the process of distribution network planning

This paper demonstrates the value of taking DSO into account in this method by comparing the planning schemes of game players under methods 1 and 3, as well as the costs and benefits.

The information in Table 5 compares the revenue from sales of electricity, investment costs, operation and maintenance costs, revenue from electricity purchases, and the total cost of goods, and services obtained by power consumers when they use methods 1 and 3 to make planning decisions.

Table 5 shows that when compared to Method 1, the total cost of power users using Method 3 for decision-making and planning is reduced by ¥363,600. This includes an increase in the income from selling electricity of ¥527,800, an increase in the cost of purchasing electricity of ¥638,600, a decrease in the investment cost of ¥386,700,

and a reduction of ¥87,600 in the cost of operation and maintenance. The reason is that the power users choose to build 150 kW DG units at nodes 5 and 6 , and do not build DG units at nodes 2, 3, and 4 when making planning decisions by using Method 1. When power users make planning decisions by using Method 3, they choose to build 100 kW DGs at nodes 2, 3, and 4, while not building new DGs at nodes 5 and 6. Further analysis shows that because Method 3 considers the price accounting mechanism of DSO, that is, considering the impact of the market price on the planning scheme, when power users employ Method 3 to make planning decisions, it results in the electricity prices of nodes 2, 3, and 4 being higher than the fixed price under Method 1, and those of nodes 5 and 6 being lower than the fixed price under Method 1. On one hand, new DG units are constructed at nodes 2, 3, and 4 in order to partially offset the electric energy purchased by power users and lessen their reliance on distribution network companies; on the other hand, at nodes 5 and 6, no more DG units are built, and only power is purchased from the distribution network operator to reduce expenses. The overall amount of DG constructed by Method 3 is smaller than that by Method 1 based on the DG construction of all nodes, resulting in an increase in the amount of power purchased from the distribution network operator. Therefore, the investment cost is lower than that by Method 1, while the cost of purchasing electricity is higher. In addition, since the power generation of the DG units built at nodes 2, 3, and 4 is greater than their node loads in Method 3, they can sell the surplus power generation to the distribution network company to increase its electricity sale revenue, while the power generation of the DG units built at nodes 5 and 6 is less than their node loads in Method 1, so the electricity sale revenue in this method is zero. Considering all the costs and expenditures, the total cost expenditure of power users is relatively small when they make decisions under the price accounting mechanism, considering DSO in Method 3.

The overall amount of DG constructed by Method 3 is smaller than that by Method 1 based on the DG construction of all nodes, resulting in an increase in the amount of power purchased from the distribution network operator. The planning and construction of DG is obtained by calculating the income and expenditure through a fixed electricity price, and the planning scheme is relatively conservative and inaccurate. When using Method 3 to make planning decisions, due to the full consideration of the guiding role of the market price, power users can accurately judge the construction of DG units according to the price of each node so as to select the appropriate power source mode, thereby reducing their own cost expenditure.

The information in Table 6 compares the distribution grid company's total revenue, investment costs, electricity costs from

TABLE 5 Comparison of the cost-benefit and total expense of power users under methods 1 and 3.

| | $C^{Use}$ (¥10,000) | $C_I^{Use}$ (¥10,000) | $C_B^{Use}$ (¥10,000) | $C_O^{Use}$ (¥10,000) | $C_S^{Use}$ (¥10,000) |
|---|---|---|---|---|---|
| **Method 1** | 3270.66 | 232.03 | 2986.06 | 52.56 | 0 |
| **Method 3** | 3234.30 | 193.36 | 3049.92 | 43.80 | 52.78 |

TABLE 6 Comparison of the cost-benefit and total revenue of the distribution network company under methods 1 and 3.

| | $C^{DN}$ (¥10,000) | $C_I^{DN}$ (¥10,000) | $C_S^{DN}$ (¥10,000) | $C_{B1}^{DN}$ (¥10,000) | $C_{B2}^{DN}$ (¥10,000) |
|---|---|---|---|---|---|
| **Method 1** | 1191.00 | 170.37 | 2986.06 | 1626.48 | 0 |
| **Method 3** | 1253.56 | 102.32 | 3049.92 | 1627.15 | 52.78 |

the main grid, cost of purchasing DG from users, and revenue from electricity sales when using methods 1 and 3 for planning and decision-making.

Table 6 demonstrates that in comparison to Method 1, the total income of the distribution network company when using Method 3 to make planning decisions has increased by ¥625,600, of which the investment cost has decreased by ¥680,500, the electricity sales income has increased by ¥638,600, the cost of purchasing electricity for the main network has increased by ¥6,700, while the cost of obtaining DG from power users has decreased by ¥527,800. The explanation is that Method 3 designs the distribution network while considering how prices will fluctuate across the board. The distribution network company does not construct new lines between nodes 1 and 2, nodes 2 and 3, and nodes 3 and 4, as a result, while utilizing Method 3 to make planning decisions. Thus, the energy rates at nodes 2, 3, and 4 are more expensive than the set rate under Method 1. As a result, power users build more DGs for their own use. New lines are built and expanded between nodes 4 and 5 and between nodes 5 and 6 so that the prices of nodes 5 and 6 are reduced, which leads to more power users buying electricity from the distribution network company to increase their electricity sales, thereby increasing their electricity sales revenue. According to the overall line construction situation, the distribution network company builds fewer lines and shorter lines when using Method 3 to make planning decisions, which leads to the reduction of its investment cost. In addition, because the power generation capacity of DG units built by power users at nodes 2, 3, and 4 is greater than their node loads under Method 3, while the power generation capacity of DG units built at nodes 5 and 6 is less than their node loads under Method 1, under Method 3, distribution network businesses pay more for their power purchases, while the power purchase cost under Method 1 is zero. Considering all the costs and expenditures, the total revenue of distribution network companies is increased when they make decisions under the price accounting mechanism, considering DSO in Method 3.

Further analysis shows that when the distribution network company uses Method 3 to make planning decisions, due to the consideration of the guiding role of market prices, on one hand, it enables the distribution network company to make a reasonable response to the market in time, and on this premise, it can choose a more accurate line expansion scheme to reduce its investment cost;

on the other hand, distribution network companies can also make accurate judgments on the new DG units of power users according to the price information of each node so as to increase their electricity sales, thereby increasing the revenue of electricity sales.

(b) Necessity analysis of considering the game in the distribution network planning process

By contrasting the planning schemes for each game subject under methods 2 and 3, as well as the costs and benefits, this research demonstrates the importance of taking the game into account.

When power users utilize methods 2 and 3 to make planning choices, the data in Table 7 show the comparison of the cost of acquiring energy, the cost of investment, the cost of operation and maintenance, and the overall cost borne by power users.

Table 7 demonstrates that in comparison to Method 3, the total cost of power users using Method 2 for decision-making and planning has increased by ¥252,900, of which the investment cost has increased by ¥386,700, the electricity sales income has increased by ¥8,000, and the electricity purchase cost has decreased by ¥220,600. The power consumers' decision to construct 100kW, 100kW, 50kW, and 50 kW DGs at nodes 2, 3, 4, and 5, respectively, while adopting Method 2 for planning and decision-making is the cause, compared with 50 kW DG units at node 5 when using Method 3 for planning and decision-making. Further analysis reveals that in comparison to Method 2, Method 3 considers the game relationship between the main bodies, allowing the distribution network company to add another line. As a result, nodes 2, 3, and 4 have prices that are marginally lower than those of Method 2, while node 5 has a price that is significantly lower than that of Method 2. Therefore, when using Method 3 to make planning decisions, power users do not choose to build a new DG unit at node 5 but choose to buy electricity from the distribution network company, resulting in an increase in the amount of electricity purchased and an increase in the cost of purchasing electricity. However, as far as the DG construction of all nodes is concerned, the planning scheme of power users using Method 3 to make decisions is less than that of Method 2 to build 50 kW DG units, which lowers the cost of maintenance and operation, as well as investment. Therefore, considering all the costs and benefits, the total cost of power users in using Method 3 to make decisions is relatively small.

**TABLE 7 Comparison of the cost-benefit and total revenue of the distribution network company under methods 1 and 3.**

|  | $C^{Use}$ (¥10,000) | $C_I^{Use}$ (¥10,000) | $C_B^{Use}$ (¥10,000) | $C_O^{Use}$ (¥10,000) | $C_S^{Use}$ (¥10,000) |
|---|---|---|---|---|---|
| Method 2 | 3259.59 | 232.03 | 3027.86 | 52.56 | 52.86 |
| Method 3 | 3234.30 | 193.36 | 3049.92 | 43.80 | 52.78 |

**TABLE 8 Comparison of the cost-benefit and total revenue of the distribution network company under methods 2 and 3.**

|  | $C^{DN}$ (¥10,000) | $C_I^{DN}$ (¥10,000) | $C_S^{DN}$ (¥10,000) | $C_{B1}^{DN}$ (¥10,000) | $C_{B2}^{DN}$ (¥10,000) |
|---|---|---|---|---|---|
| Method 2 | 1291.84 | 56.04 | 3027.86 | 1627.12 | 52.86 |
| Method 3 | 1253.56 | 102.32 | 3049.92 | 1627.15 | 52.78 |

The data provided in Table 8 show the comparison of the distribution grid company's total revenue, investment costs, electricity costs from the main grid, cost of purchasing DG from users, and revenue from electricity sales when using methods 2 and 3 for planning and decision-making, respectively.

Table 8 demonstrates that in comparison to Method 3, the distribution network company's overall revenue increased when using Method 2 for planning and decision-making, which has increased by ¥382,800, of which the investment cost has decreased by ¥462,800, the electricity sales income has decreased by ¥220,600, the price of purchasing power from the primary grid has decreased by ¥3,000, but the cost of buying DG from power consumers has increased by ¥8,000. The reason is that Method 2 is a distribution network planning method without considering the game relationship between the main bodies, and it seeks to maximize the shared interests of power customers and distribution network companies. The increase in the total revenue of distribution network companies is obtained at the expense of the interests of power users. When the distribution network company uses Method 3 to make planning decisions, it considers the game relationship between market players, and its planning scheme is obtained from the perspective of individual interests. Therefore, a new line is constructed between nodes 4 and 5, which evidently lowers the cost of node 5 and raises revenue from electricity sales by increasing the sales of electricity. At the same time, the cost of building additional expansion lines has increased, and as a result, when all expenses and advantages are taken into account, the distribution network company's overall benefit is lower when using Method 3.

The data in Table 9 show the comparison of the overall expenditure of the distribution company and the power user when they make planning decisions using methods 2 and 3. The overall expenditure $C^{SUM}$ is computed by summing the total cost and revenue of the distribution network operator, and the total cost and revenue of power customers.

Table 9 demonstrates that, in comparison to Method 3, the overall expenditure of each entity when using Method 2 to make planning decisions is reduced by ¥129,900, but the cost expenditure of power users is increased by ¥252,900. Because Method 2 is a distribution network design method, it maximizes the interests of both power customers and distribution network corporations as a whole, so their overall cost expenditure is optimal. The result of pursuing the optimal overall expenditure is bound to sacrifice the interests of some market

**TABLE 9 Comparison of the total expenditures of power users and distribution companies under methods 2 and 3.**

|  | $C^{Use}$ (¥10,000) | $C^{DN}$ (¥10,000) | $C^{SUM}$ (¥10,000) |
|---|---|---|---|
| Method 2 | 3259.59 | 1291.84 | 1967.75 |
| Method 3 | 3234.30 | 1253.56 | 1980.74 |

players, so the increase in the distribution network company's revenue in Method 2 is at the expense of the interests of power users. However, in the electricity market environment, each market's main body takes its own benefit maximization as the goal in the planning process, and the electricity users with individual rational characteristics find it impossible to increase their own cost expenditure in order to optimize the overall expenditure. This planning method does not conform to the actual operation mechanism of the electricity market; it can not only obtain an accurate and effective planning scheme but also disrupt the market order and affect the stable operation of the electricity market. When each agent uses Method 3 to make decisions, its decision-making method is based on a continuous game, and no participant can improve outcomes by altering their own approach. This method takes into account the interests of all parties; not only can it obtain a more accurate planning scheme but can also ensure the fairness of the whole electricity market competition so as to stimulate market vitality and improve the efficiency of resource allocation.

## 6 Conclusion

This study proposes a strategy for planning distribution networks that takes into consideration the multi-agent games and distribution system operators. Using the power distribution market's planning and operating mechanisms, a multi-agent game planning model that takes market pricing into account is developed. In the end, the iterative search methodology is used to solve the model. The paper's precise conclusions are as follows.

(1) Compared with the traditional methods, the proposed distribution network planning method considering distribution system operators and the multi-agent game not

only considers the guiding role of market price but also considers the game relationship of market players. In the process of a continuous game, market players can still consider the impact of market prices, and this enhances planning and decision-making's efficacy and precision.

(2) This research develops a distribution network planning model based on the theory of the nodal marginal pricing of the distribution network, taking into account the distribution system operators and multi-agent game in view of changes in the market price during the distribution network planning process so that each agent can make a rapid and reasonable response to the market, thus improving the vitality of the market and the efficiency of power resource allocation.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## Author contributions

JL, ST, JJ, and SC contributed to the conception and design of the study. ST organized the database. JJ performed the statistical analysis. JL wrote the first draft of the manuscript. TW and SC wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

Authors JL, TW, ST, JJ, and SC were employed by the China Southern Power Grid.

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