IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 16, 2020, accepted April 14, 2020, date of publication April 29, 2020, date of current version May 22, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2991181

Multi-Lateral Participants Decision-Making: A Distribution System Planning Approach With Incomplete Information Game

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This work was supported in part by the National Natural Science Foundation of China under Grant 51607104, and in part by the China Scholarship Council.

ABSTRACT Competition on distributed generation (DG) investments among multiple stakeholders in a distribution system results in incompleteness of market information, in which each stakeholder does not have full knowledge on investment and operation decisions of other participants. It leads to an incomplete information game among multiple stakeholders. This paper discusses a multi-lateral incomplete information game based approach to study distribution system planning while considering both supply and demand sides competitions. Profit models of three types of stakeholders, including DG investors (i.e., DG units are investor-owned), electricity consumers, and the distribution company, are constructed. The interaction among the stakeholders and their gaming behavior are further studied under the context of multi-lateral incomplete information. Bayesian Nash equilibrium form of the multi-lateral incomplete information game is obtained via Harsanyi transformation. An improved co-evolutionary algorithm is adopted to find the Bayesian Nash equilibrium. Simulation results on a modified IEEE 33-bus test system show that, compared with the complete information game method, the proposed approach presents higher expected profits and more accurate planning schemes. Indeed, the proposed approach reflects the realistic planning process of distribution systems under a deregulated competitive environment, and it ensures fairness of competition among self-interested independent stakeholders while guaranteeing their individual performance.

INDEX TERMS Distribution system planning, multi-lateral incomplete information game, Bayesian Nash equilibrium, Harsanyi transformation, co-evolutionary algorithm.

NOMENCLATURE

A. INDICES

a	Index of distributed generation (DG) investors
b	Index of demand response incentive compensation schemes (DRICSs)
c	Index of Distribution Companies (DisCos)
t	Index of hours in a typical day
day	Index of typical days

The associate editor coordinating the review of this manuscript and approving it for publication was Fabio Mottola.

B. SETS

A	Set of DG investors
B	Set of DRICSs
C	Set of DisCos
T	Set of hours in a typical day
Ω_{day}	Set of typical days
Ω	Set of buses which DG are connected to
Θ	Set of candidate lines to be enhanced
Ψ	Set of buses of DR capacities
$\boldsymbol{O}_{-\mathrm{a}}$	Set of game type variable excluding DG investors
$\boldsymbol{O}_{-\mathrm{b}}$	Set of game type variable excluding electricity consumers
$\boldsymbol{O}_{-\mathrm{c}}$	Set of game type variable excluding the DisCo

C. PARAMETERS

θ_1^a	Electricity selling price of DG investor a
θ_2^a	Generation subsidy price of DG investor a
θ_3^a	Per unit capacity price of investment cost of DG investor a
θ_4^a	Per unit capacity price of operation and maintenance cost of DG investor a
$C_{DG,S}^a$	Income of electricity sale of DG investor a
$C_{DG,C}^a$	Income of generation subsidy of DG investor a
$C_{DG,I}^a$	Investment cost of DG investor a
$C_{DG,OM}^a$	Operation and maintenance costs of DG investor a
$P_{DG}^a(t, day)$	Active power of DGs from DG investor a at time t in a typical day
r	Discount rate
LT_1	Life time of DG equipment
LT_2	Life time of line
$N_{\min}^a$	Minimum DG capacity of DG investor a connected to bus m
$N_{\max}^a$	Maximum DG capacity of DG investor a connected to bus m
δ	Penetration of DGs
P_{total}	Total load of the distribution system
$P_{\min}^a$	Minimum output of DGs for DG investor a
$P_{\max}^a$	Maximum output of DGs for DG investor a
ω_1^b	Power purchasing price of consumers of DRICS b
ω_2^b	Interruptible load compensation price of consumers of DRICS b
$C_{US,B}^b$	Reduced electricity cost of consumers of DRICS b
$C_{US,C}^b$	Interruptible load compensation revenue of consumers of DRICS b
σ	A parameter reflects the load adjustment ratio in a typical day
$\lambda_{\min}$	Minimum ratio of increased load
$\lambda_{\max}$	Maximum ratio of increased load
$\mu_{\min}$	Minimum ratio of decreased load
$\mu_{\max}$	Maximum ratio of decreased load
l_n	Length of line n
$P_{load}(t, day)$	Original system load at time t
$P_{loss}(t, day)$	Active power loss at time t in a typical day
φ_1	Electricity selling price of DisCo
φ_2	Per unit length price of lines to be enhanced
φ_3	Per unit capacity price of DR cost
φ_4	Electricity purchase price from the main grid
φ_5	Electricity purchase price from DG investors
$C_{DN,S}$	Income of electricity sale of DisCo
$C_{DN,I}$	Cost of lines to be enhanced
$C_{DN,L}$	Cost related to network losses
$C_{DN,R}$	DR cost
$C_{DN,B1}$	Cost of purchasing power from the main grid
$C_{DN,B2}$	Cost of purchasing power from DG investors
$DR_{k,\max}$	Maximum DR capacity at bus k
$P_{i,t,day}$	Active power of bus i at time t in a typical day
$Q_{i,t,day}$	Reactive power of bus i at time t in a typical day
$U_{i,t,day}$, $U_{j,t,day}$	Voltage amplitude of bus i/j at time t in a typical day
G_{ij}	Conductance of line (i,j)
B_{ij}	Susceptance of line (i, j)
$\theta_{ij,t,day}$	Voltage phase angle difference between buses i and j at time t in a typical day
$\theta_{ij,\min}$	Minimum voltage phase angle difference between buses i and j
$\theta_{ij,\max}$	Maximum voltage phase angle difference between buses i and j
$U_{i,\min}$	Minimum voltage amplitude of bus i
$U_{i,\max}$	Maximum voltage amplitude of bus i
$P_{ij,t,day}$	Power flow from bus i to j at time t in a typical day
$P_{ij,\max}$	Power flow limit of line (i, j)
$\rho(tp)$	Probabilities of all players
$\rho(a)$	Probability of DG investor a
$\rho(b)$	Probability of consumer of DRICS b
$\rho(c)$	Probability of the DisCo
$\rho(tp_{-\mathrm{a}} \vert a)$	Conditional probability of $tp_{-\mathrm{a}}$ when DG investor is a
$\rho(tp_{-\mathrm{b}} \vert b)$	Conditional probability of $tp_{-\mathrm{b}}$ when consumer choose DRICS b
$\rho(tp_{-\mathrm{c}} \vert c)$	Conditional probability of $tp_{-\mathrm{c}}$ when the DisCo is c
E_{DG}^*	Expected profit of DG investors
E_{US}^*	Expected profit of electricity consumers
E_{DN}^*	Expected profit of the DisCo
H	Evolution generation H
F_H	Individual fitness in generation H
R_1	Species of DG investors
R_2	Species of electricity consumers
R_3	Specie of the DisCo
R_1^a	Population of DG investor a
R_2^b	Population of electricity consumer with DRICS b
R_3^c	Population of the DisCo
f	Relation mapping individual to strategy

D. VARIABLES

x_m^a	Binary variable of DG locations
N_m^a	Total DG capacities of DG investor a connected to bus m

$P^b_{decrease}(t, day)$	Decreased load of DRICS b at time t in a typical day
$P^b_{increase}(t, day)$	Increased load of DRICS b at time t in a typical day
$P^b_{interrupt}(t, day)$	Interruptible load of consumers of DRICS b at time t in a typical day
y_n	Binary variable of candidate lines to be enhanced
D_k	Capacity of DRs connected to bus k ‘
tp	Game type variable
$tp_{-\mathrm{a}}$	Game type variable excluding DG investors
$tp_{-\mathrm{b}}$	Game type variable excluding consumers
$tp_{-\mathrm{c}}$	Game type variable excluding the DisCo
S^*	Bayesian Nash equilibrium
S'_a	A strategy of DG investor a
S'_b	A strategy of electricity consumers with DRICS b
S'_c	A strategy of the DisCo
$R^a_{1\mathrm{r}}$	Representative of population R^a_1
$R^b_{2\mathrm{r}}$	Representative of population R^b_2
$R^c_{3\mathrm{r}}$	Representative of population R^c_3
$R^a_{1\mathrm{n}}$	An individual in population $R^a_1 \backslash R^a_{1\mathrm{r}}$
$R^b_{2\mathrm{n}}$	An individual in population $R^b_2 \backslash R^b_{2\mathrm{r}}$
$R^c_{3\mathrm{n}}$	An individual in population $R^c_3 \backslash R^c_{3\mathrm{r}}$

I. INTRODUCTION

The ever-growing electricity market is gradually open for participants in distribution systems [1], [2]. Indeed, a large number of distributed generations (DGs), energy storage, controllable loads, and electric vehicles have emerged in distribution systems, making electricity market more open, complex, and diverse [3]. This complex competition environment of electricity market is shown in Fig.1.

- On the supply side, the DGs connected to the distribution system are investor-owned, and their power generation will be consumed by customers in the Distribution Company (DisCo) preferentially [4]–[7]. Indeed, multiple investors would compete for the right of DG investment and operation to pursue maximum profits.
- On the grid side, the DisCo is responsible for construction and safe operation of the distribution network. The DisCo is not responsible for dispatching DGs, but is in charge of managing the network to absorb these active power injections [4]. It plays a role of buying all electricity from DGs, selling to users, and determining charge rates.
- On the demand side, power retailers aggregate electricity consumers and trade electricity with the DisCo on behalf of these consumers [8]. In a distribution system, multiple potential stakeholders offer distinct demand response incentive compensation schemes (DRICSs), competing with each other to become a power retailer [9]–[13]. These DRICSs will derive different demand response (DR) load adjustment results [14]–[17].

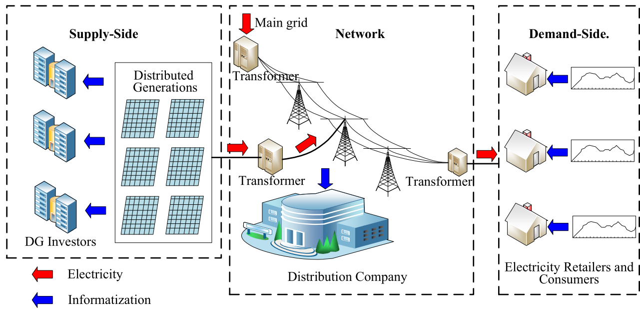

FIGURE 1. The competitive environment in distribution systems.

Under the environment described above, the peer competition with information asymmetry results in a significant challenge to the distribution system planning, in terms of different stakeholders. Consequently, under the background of an open distribution electricity market, it is of great practical significance to study the distribution system planning while considering the multi-lateral incomplete information game [18]–[20] of the stakeholders from both supply and demand sides.

Game theory based distribution system planning approaches have been previously studied, and attention-grabbing planning models have been proposed [21]–[27]. A Cournot game model is proposed in [23] to analyze the amount of wind generation in a concentrated energy-only market. Reference [24] discusses a method to find the optimal location and operation strategy of DGs simultaneously. Game theory is employed in this method to assist the optimal contract prices. In reference [25], the interaction between the DisCo and DG investors is analyzed, and a two-layer Stackelberg game model is proposed. In this model, the DisCo is taken as the game leader to plan the distribution network, and the DG investors are considered as the game followers for DG locating and sizing. These models can clearly describe the gaming relationship among self-interested independent participants, and help understand different perspectives in the planning process. However, they are all complete information game based planning approach. That is, these approaches work for the situation that no competitor in the same type of stakeholders exists and information is fully shared among different players.

In practice, there could be multiple competitors in the same type of market stakeholder. For instance, multiple DG investors could compete for DG investment and operation in a target distribution grid. To this end, in the planning stage, a DG investor shall consider planning strategies of other DG investors. In addition, for other game players (such as the DisCo), they do not have full information as of which DG investor will ultimately invest and operate the DGs. That is, a competitor has an incomplete knowledge of other competitors' planning information. Therefore, the effectiveness and accuracy of complete information game based planning methods cannot be guaranteed in the above described distribution system. It is necessary to consider incomplete information among heterogeneous participants in the planning process.

Incomplete information game theory has been preliminarily applied in distribution network planning [28]. In reference [28], a two-layer model of unilateral incomplete information game is established to determine generation expansion planning strategies. The upper layer is based on an incomplete information game to determine generation capacity and bid. Nonetheless, the weakness of this model is that incomplete information about multiple competitors of the power supply-side is only considered in the upper layer, while optimal strategy determinations of other decision-making participants are presented based on a complete information game. Practically, incomplete information exists among numerous participants in an opening electricity market [34], with multiple competitors of DG investors on the supply side and multiple power retailers on the demand side. This leads to different DRICSs chosen by electricity consumers. From the above descriptions, it is clear that the incomplete information is multi-lateral. Hence, the game of distribution system planning is a complex multi-lateral incomplete information game, while the related research has been rarely reported.

In this paper, a distribution system planning approach is proposed, while considering multi-lateral incomplete information game on both supply and demand sides. Profit models of three types of stakeholders, including DG investors, electricity consumers, and the DisCo, are first constructed. The interaction among the stakeholders and their gaming behavior are further studied. Moreover, the Bayesian Nash equilibrium form of the multi-lateral incomplete information game is derived via the Harsanyi transformation. Finally, an improved co-evolutionary algorithm is utilized to find the Bayesian Nash equilibrium, which is the optimal solution to the planning problem.

The main contributions of the paper are summarized as follows:

- In observing the recent development of electricity market in distribution systems, a multi-lateral incomplete information game model is innovatively employed to solve the distribution system planning problem. The proposed approach reflects the realistic planning process of distribution systems in a deregulated competitive environment. Furthermore, the proposed planning approach derives higher expected profits than those from the complete information game models, and promotes more reasonable and accurate planning schemes.
- Compared with unilateral incomplete information game, the proposed approach is based on multi-lateral stakeholders in both supply and demand sides. Consequently, the fairness of self-interested independent stakeholders to pursue individual performance objectives can be guaranteed. Moreover, peer competition among stakeholders to invest and construct the distribution system can be motivated.

The rest of the paper is organized as follows. Profit models of three types of players, including DG investors, electricity consumers, and the DisCo, are given in Section II. The interaction among the stakeholders and their gaming behavior are analyzed in Section III. The co-evolutionary algorithm based solution methodology is presented in Section IV. Numerical simulation results are performed in Section V, and conclusions are drawn in Section VI.

II. PROFIT MODELS OF THREE TYPES OF STAKEHOLDERS

Three types of stakeholders, on the supply, network, and demand sides, are involved in the planning and operation of the distribution system. To this end, the DG investors, electricity consumers, and the DisCo act as game players, pursuing their own maximum profits by reducing costs and increasing revenues.

A. DG INVESTORS

The profit model of DG investors focuses on determining the optimal locations and capacities of DG in the distribution system to maximize their profits [29], [30].

- Objective Function

To determine the optimal DG locations and capacities, the objective function of DG investor a includes the electricity sale income, generation subsidy income, investment cost, and operation and maintenance (O&M) cost, as shown as Eq.(1)-(5).

$$C_{DG}^{a}(x_{m}^{a}, N_{m}^{a}) = C_{DG,S}^{a} + C_{DG,C}^{a} - (C_{DG,I}^{a} + C_{DG,OM}^{a}), \quad a \in A \tag{1}$$

where a is DG investor; A is the set of DG investors; x_{m}^{a} is a binary variable about DG locations, which is equal to 1 when DG investor a puts DG at bus m, and is 0 otherwise; N_{m}^{a} is total DG capacities of DG investor a connected to bus m; C_{DG}^{a} mean the total profit of DG investor a; $C_{DG,S}^{a}$, $C_{DG,C}^{a}$, $C_{DG,I}^{a}$ and $C_{DG,OM}^{a}$ represent the electricity sale income, generation subsidy income, investment cost and O&M cost of DG investor a respectively.

$$C_{DG,S}^{a} = \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} \theta_{1}^{a} \cdot P_{DG}^{a}(t, day) \tag{2}$$

where θ_{1}^{a} is electricity selling price of DG investor a; t is time; T is the set of time t; day is a typical day; Ω_{day} is the set of day; $P_{DG}^{a}(t,day)$ represent active power of DGs from DG investor a at time t in a typical day.

$$C_{DG,C}^{a} = \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} \theta_{2}^{a} \cdot P_{DG}^{a}(t, day) \tag{3}$$

where θ_{2}^{a} is generation subsidy price of DG investor a.

$$C_{DG,I}^{a} = (\theta_{3}^{a} \cdot \sum_{m=1}^{\Omega} x_{m}^{a} \cdot N_{m}^{a}) \cdot \frac{r(1+r)^{LT_1}}{(1+r)^{LT_1} - 1} \tag{4}$$

where θ_{3}^{a} is per unit capacity price of investment cost of DG investor a; Ω is the set of bus m which DG are connected to;

r is discount rate; LT_1 means life time of DG equipment.

$$C^a_{DG,OM} = \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} \theta^a_4 \cdot P^a_{DG}(t, day) \quad (5)$$

where θ^a_4 is per unit capacity price of O&M price of DG investor a.

- Constraints

A set of technical constraints related to DG locations and capacities are described as follows:

1) DG CAPACITY LIMIT

The operating range of DG at bus m shall be within acceptable limits because of investor's budget as described in (6).

$$N^a_{\min} \le N^a_m \le N^a_{\max} \quad (6)$$

where $N^a_{\min}$ and $N^a_{\max}$ represent minimum and maximum DG capacity limit of DG investor a connected to bus m respectively.

2) PENETRATION LEVEL OF DGS

The total installed DG capacity shall be no larger than its permitted value as in (7). The preset penetration level δ refers to ratio of the total allowed DG capacity to rated capacity of the distribution system.

$$\sum_{m=1}^{\Omega} x^a_m \cdot N^a_m \le \delta \cdot P_{total} \quad (7)$$

where δ is DGs penetration; P_{total} is total load of the distribution system.

3) DG OUTPUT LIMIT

The range of DG outputs at time t should be kept within physical operating ranges as in (8).

$$P^a_{\min} \le P^a_{DG}(t, day) \le P^a_{\max} \quad (8)$$

where $P^a_{\min}$ and $P^a_{\max}$ mean minimum and maximum output of DGs for DG investor a at time t in a typical day respectively.

B. ELECTRICITY CONSUMERS

Power retailers trade electricity with the DisCo on behalf of the electricity consumers. In a region, multiple potential stakeholders with distinct DRICSs would compete to become the power retailer of this region. Electricity consumers in this region adjust load flexibly by the finalized DRICSs to reduce their electricity costs [31]. The profit model of electricity consumers aims at determining the amount of adjustable load in the distribution system to maximize their profits.

- Objective Function

The objective function of electricity consumers with DRICS b includes the reduced electricity expense and interruptible load compensation income, as shown in Eq. (9)-(11).

$$C^b_{US}(P^b_{increase}(t, day), P^b_{decrease}(t, day), P^b_{interrupt}(t, day)) = C^b_{US,B} + C^b_{US,C}, b \in B \quad (9)$$

where $P^b_{increase}(t,day)$, $P^b_{increase}(t,day)$ and $P^b_{interrupt}(t,day)$ are increased, decreased and interruptible load of consumers of DRICS b at time t in a typical day respectively; C^b_{US} is the total profit of consumers of DRICS b; B is the set of DRICS b; $C^b_{US,B}$ and $C^b_{US,C}$ represent reduced electricity expense and interruptible load compensation income respectively.

$$C^b_{US,B} = \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} \omega^b_1 \cdot (P^b_{decrease}(t, day) - P^b_{increase}(t, day)) \quad (10)$$

where ω^b_1 is power purchasing price of consumers of DRICS b.

$$C^b_{US,C} = \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} \omega^b_2 \cdot P^b_{interrupt}(t, day) \quad (11)$$

where ω^b_2 is interruptible load compensation price of consumers of DRICS b.

- Constraints

1) LOAD ADJUSTMENT LIMITS

Although DR characteristics of individual loads are different, the total load adjustment capabilities of DRICS b are limited via lower and upper bounds as in (12).

$$\begin{cases} \lambda_{\min} \sum_{k=1}^{\Psi} D_k \le P^b_{increase}(t, day) \le \lambda_{\max} \sum_{k=1}^{\Psi} D_k \\ \mu_{\min} \sum_{k=1}^{\Psi} D_k \le P^b_{decrease}(t, day) \le \mu_{\max} \sum_{k=1}^{\Psi} D_k \end{cases} \quad (12)$$

where D_k is the capacity of DRs connected to bus k; Ψ is the set of buses of DR capacities; $\lambda_{\min}$ and $\lambda_{\max}$ are minimum and maximum ratio of increased load; $\mu_{\min}$ and $\mu_{\max}$ are minimum and maximum ratio of decreased load respectively.

2) LOAD BALANCE

The load balance after DR in a typical day can be described as in (13). In (13), parameter σ reflects the load adjustment ratio in a typical day: $\sigma > 1$ indicates that the load reduction is more than the increase; $\sigma = 1$ shows that the two values are equal; $\sigma < 1$ indicates that the load reduction is less than the increase, i.e., certain loads are curtailable.

$$\sum_{t=1}^{T} P^b_{decrease}(t, day) - \sigma \sum_{t=1}^{T} P^b_{increase}(t, day)) = 0 \quad (13)$$

C. DISTRIBUTION COMPANY

The profit model of the DisCo targets on determining the optimal planning of distribution lines in a radial distribution system and signing DR capacities with electricity retailers [32], [33].

- Objective Function

To determine optimal line investment and DR capacities, the objective function of the DisCo includes the electricity sale income, the line construction cost, the network loss cost, the signed DR capacity cost, the power purchase expense from the main grid, and the power purchase expense from

DG investors, as shown in Eq.(14)-(20).

$$C_{DN}(y_n, D_k) = C_{DN,S} - (C_{DN,I} + C_{DN,L} + C_{DN,R} + C_{DN,B1} + C_{DN,B2}) \quad (14)$$

where y_n is a binary variable, which is 1 if line n is enhanced and is 0 otherwise; C_{DN} is the total profit of the DisCo; $C_{DN,S}$, $C_{DN,I}$, $C_{DN,L}$, $C_{DN,R}$, $C_{DN,B1}$ and $C_{DN,B2}$ are the electricity sale income, the line construction cost, the network loss cost, the signed DR capacity cost, the power purchase expense from the main grid, and the power purchase expense from DG investors respectively.

$$C_{DN,S} = \varphi_1 \cdot \left(\sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} P_{load}(t, day) - \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} (P^b_{decrease}(t, day) - P^b_{increase}(t, day)) \right) \quad (15)$$

where φ_1 is electricity selling price of the DisCo; $P_{load}(t,day)$ is original system load at time t.

$$C_{DN,I} = (\varphi_2 \cdot \sum_{n=1}^{\Theta} y_n \cdot l_n) \cdot \frac{r(1+r)^{LT_2}}{(1+r)^{LT_2} - 1} \quad (16)$$

where φ_2 is per unit length price of lines to be enhanced; l_n is length of line n; Θ is the set of candidate lines to be enhanced; LT_2 is life time of line.

$$C_{DN,L} = \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} \varphi_1 \cdot P_{loss}(t, day) \quad (17)$$

where $P_{loss}(t,day)$ is active power loss at time t in a typical day.

$$C_{DN,R} = \sum_{k=1}^{\Psi} \varphi_3 \cdot D_k \quad (18)$$

where φ_3 is per unit capacity price of DR cost.

$$C_{DN,B1} = \varphi_4 \cdot \left(\sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} (P_{load}(t, day) - P^a_{DG}(t, day)) - \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} (P^b_{decrease}(t, day) - P^b_{increase}(t, day)) \right) \quad (19)$$

where φ_4 is electricity purchase price from the main grid.

$$C_{DN,B2} = \sum_{day=1}^{\Omega_{day}} \sum_{t=1}^{T} \varphi_5 \cdot P^a_{DG}(t, day) \quad (20)$$

where φ_5 is electricity purchase price from DG investors.

- Constraints

The following constraints are considered in the DisCo's problem.

1) DR CAPACITY LIMIT

There total DR capacities signed with consumers cannot exceed the maximum value because of physical limitations of network to accommodate DR.

$$\begin{cases} \sum_{k=1}^{\Psi} D_k \le \sum_{k=1}^{\Psi} DR_{k,\max} \\ D_k \le DR_{k,\max} \end{cases} \quad (21)$$

where $DR_{k,\max}$ is maximum DR capacity at bus k.

2) LOAD BALANCE CONSTRAINT

The active and reactive power balance should be maintained at each bus, as in (22).

$$\begin{cases} P_{i,t,day} = U_{i,t,day} \cdot \sum_{j \in i} U_{j,t,day} \cdot (G_{ij} \cdot \cos\theta_{ij,t,day} + B_{ij} \cdot \sin\theta_{ij,t,day}) \\ Q_{i,t,day} = U_{i,t,day} \cdot \sum_{j \in i} U_{j,t,day} \cdot (G_{ij} \cdot \sin\theta_{ij,t,day} - B_{ij} \cdot \cos\theta_{ij,t,day}) \end{cases} \quad (22)$$

where $P_{i,t,day}$ and $Q_{i,t,day}$ are active and reactive power of bus i at time t in a typical day respectively; $U_{i,t,day}$ and $U_{j,t,day}$ are voltage amplitude of bus i and j at time t in a typical day; G_{ij} and B_{ij} are conductance and susceptance of line between buses i and j; $\theta_{ij,t,day}$ is voltage phase angle difference between buses i and j at time t in a typical day.

3) NETWORK SECURITY CONSTRAINT

The bus voltage magnitudes and phase angles shall be kept within acceptable operating ranges. Power flows of lines shall also remain within the safe range.

$$\begin{cases} U_{i,\min} \le U_{i,t,day} \le U_{i,\max} \\ \theta_{ij,\min} \le \theta_{ij,t,day} \le \theta_{ij,\max} \\ P_{ij,t,day} \le P_{ij,\max} \end{cases} \quad (23)$$

where $\theta_{ij,\min}$ and $\theta_{ij,\max}$ are minimum and maximum voltage phase angle difference between buses i and j; $U_{i,\min}$ and $U_{i,\max}$ are minimum and maximum voltage amplitude of bus i respectively; $P_{ij,t,day}$ is power flow from bus i to j at time t in a typical day; $P_{ij,\max}$ is power flow limit of line between buses i and j.

III. THE INCOMPLETE INFORMATION GAMING BEHAVIOR

A. THE INTERACTION AMONG THE STAKEHOLDERS

In the distribution system planning, the three types of main stakeholders, including DG investors, the DisCo, and electricity consumers, respectively determine optimal plans for new DG units, distribution lines, DRs and adjustable load. Indeed, under the electricity market environment, the three types of main stakeholders will influence each other's planning decisions. For instance, locations and capacities of DG for DG investors can affect the investment of lines and profits from trading electricity power with the DisCo;

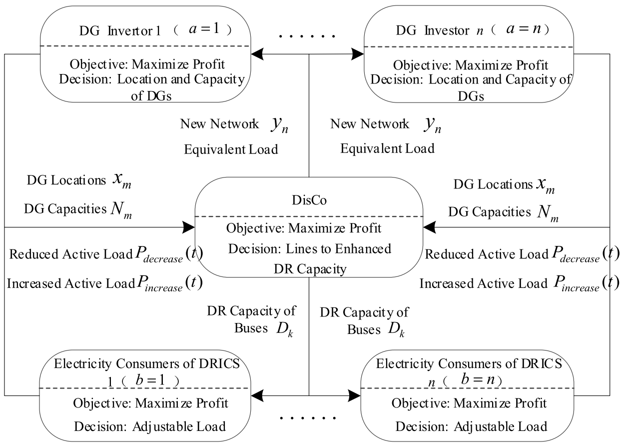

FIGURE 2. **The interaction among stakeholders.**

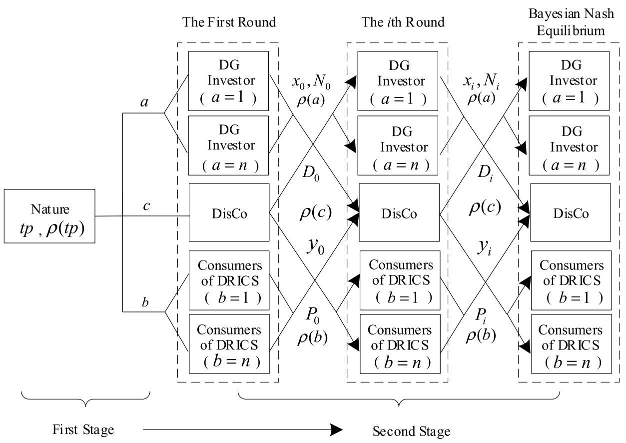

FIGURE 3. **The incomplete information gaming behavior of players.**

the DR capacities of DisCo can directly affect adjustable loads for electricity consumers; the line planning of the DisCo and the equivalent load after consumers' adjustment can affect locations and capacities of DG for DG investors. The interactive relationship among all stakeholders is shown in Fig. 2, which would impact the decision making collectively.

B. INCOMPLETE INFORMATION GAME BEHAVIOR

Multiple competitors of DG and DRs result in incompleteness of market information. Peer competition leads to the uncertainty that a type of stakeholders is uncertain about how other stakeholders participate in the planning process. That is, it is not clear which DG investor will invest and operate DG and which DRICS will be signed by electricity consumers. This information incompleteness will affect all players' planning decisions. To solve the issue, a virtual player "nature" is introduced through Harsanyi transformation [34]–[36]. "Nature" will determine a game type variable that describes probabilities of individual players participating the distribution system planning through the game. The specific gaming behavior is shown in Fig. 3.

The process of gaming behavior is divided into two stages.

1) FIRST STAGE

DG investors, DRICSs, and DisCo are numbered in sequence. A game type variable is set as "nature", defined as:

$$tp = (a, b, c), \quad a \in A,\ b \in B,\ c = 1 \tag{24}$$

Probability distribution $\rho(tp)$ describes the probability of DG investor a, DRICS b and the DisCo in participating in the distribution system planning. In addition, $tp_{-\mathrm{a}}$ refers as a game type variable excluding DG investors as in (25). Similarly, $tp_{-\mathrm{b}}$ and $tp_{-\mathrm{c}}$ are game type variables excluding electricity consumers and the DisCo respectively.

$$tp_{-\mathrm{a}} = (b, c), \quad b \in B,\ c = 1,\ tp_{-\mathrm{a}} \in \boldsymbol{O}_{-\mathrm{a}} \tag{25}$$

2) SECOND STAGE

Bayes Criterion is used to calculate the conditional probability distribution of each participant. Then, self-planning schemes are decided by each player to pursue individual maximal expected profit. When the strategy combination is S^*, the expected profits of DG investors, electricity consumers, and the DisCo are described as follows:

$$\begin{cases} E^*_{DG}(S^*_a, S^*_{tp_{-\mathrm{a}}}) = \sum\limits_{a\in A}\ \sum\limits_{tp_{-\mathrm{a}}\in O_{-\mathrm{a}}} \rho(a) C^a_{DG}(S^*_a, S^*_{tp_{-\mathrm{a}}}) \\ \qquad \times \rho(tp_{-\mathrm{a}}\,|a) \\ E^*_{US}(S^*_b, S^*_{tp_{-\mathrm{b}}}) = \sum\limits_{b\in B}\ \sum\limits_{tp_{-\mathrm{b}}\in O_{-\mathrm{b}}} \rho(b) C^b_{US}(S^*_b, S^*_{tp_{-\mathrm{b}}}) \\ \qquad \times \rho(tp_{-\mathrm{b}}\,|b) \\ E^*_{DN}(S^*_c, S^*_{tp_{-\mathrm{c}}}) = \sum\limits_{c=1}\ \sum\limits_{tp_{-\mathrm{c}}\in O_{-\mathrm{c}}} \rho(c) C_{DN}(S^*_c, S^*_{tp_{-\mathrm{c}}}) \\ \qquad \times \rho(tp_{-\mathrm{c}}\,|c) \end{cases} \tag{26}$$

The optimal strategies of all players constitute the Bayesian Nash equilibrium S^*. It means that, at this equilibrium, no player has incentive to change its planning strategy. The expected profits are described as follows:

$$\begin{cases} E^*_{DG}(S^*_a, S^*_{tp_{-\mathrm{a}}}) = \max\limits_{S'_a} E^*_{DG}(S'_a, S^*_{tp_{-\mathrm{a}}}) \\ E^*_{US}(S^*_b, S^*_{tp_{-\mathrm{b}}}) = \max\limits_{S'_b} E^*_{US}(S'_b, S^*_{tp_{-\mathrm{b}}}) \\ E^*_{DN}(S^*_c, S^*_{tp_{-\mathrm{c}}}) = \max\limits_{S'_c} E^*_{DN}(S'_c, S^*_{tp_{-\mathrm{c}}}) \end{cases} \tag{27}$$

IV. SOLUTION METHODOLOGY VIA COEVOLUTION ALGORITHM

Enlightened by the concept of coevolution in the ecosystem, co-evolutionary algorithm [28], [37]–[40] has been used to solve optimization problems involving multiple interacting individuals. In this paper, we improve the co-evolutionary algorithm in literature [28] for solving unilateral incomplete information game to calculate Bayesian Nash equilibrium. Three types of stakeholders, including DG investors, electricity consumers, and the DisCo, constitute three species, and each player is set as a population in these species. Locations and capacities of DG, line investment decision, as well as DR capacities and adjustment loads are encoded as individuals in different species. Each individual runs the standard Genetic

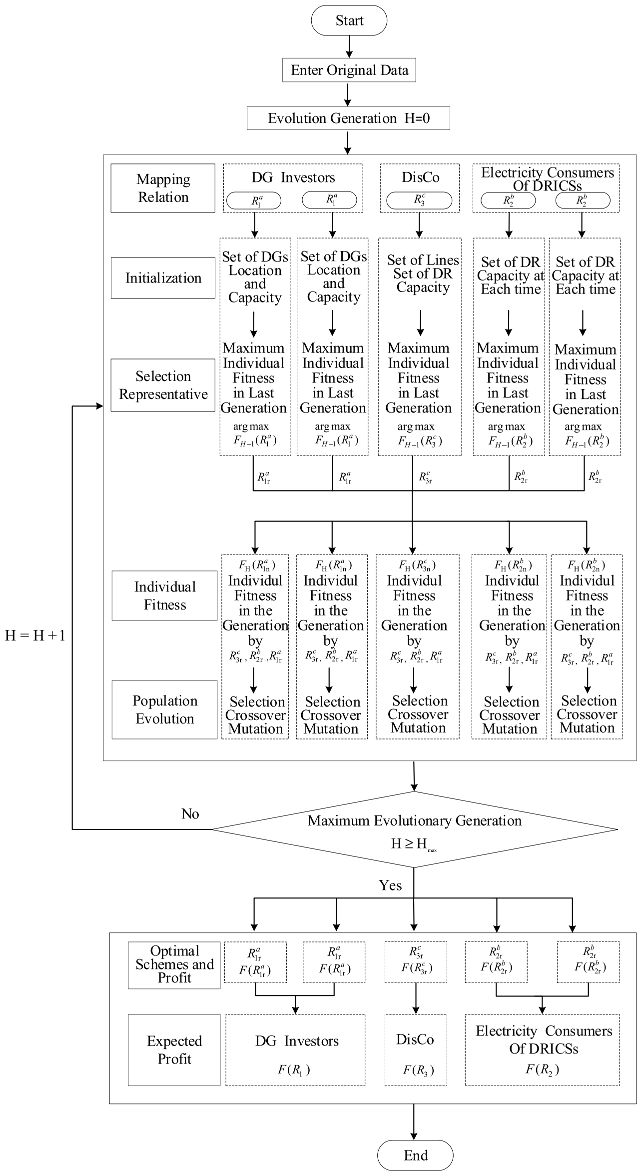

FIGURE 4. **The process of the improved co-evolutionary algorithm.**

Algorithm to search for its own best fitness and optimal planning decision. All individuals conduct their evolution through standard genetic operations, such as selection, crossover and mutation. This iterative process continues until certain termination conditions (All individuals conduct maximal evolutionary generation $H_{\max}$) are satisfied. The detailed process is shown in Fig. 4.

A. MAPPING RELATION

Three types of stakeholders are established with corresponding species R_1, R_2 and R_3. These species include R_1^a, R_2^b and R_3^c corresponding to population DG investors, electricity consumers, and the DisCo.

B. INITIALIZATION

Decision variables of various populations are encoded as individual with corresponding ranges. Each decision variable is randomly initialized within its range.

C. SELECTION OF REPRESENTATIVES

A single specie or its population is a part of the global solution in this algorithm. Individuals in its population are evaluated by information of other species. Therefore, in this process, the elite representation mechanism is adopted. For the H^{th} generation, the representatives $R_{1\mathrm{r}}^a$, $R_{2\mathrm{r}}^b$, and $R_{3\mathrm{r}}^c$ are the individuals that are the best fitness in the $(H-1)^{th}$ generation. The specific expression are as follows:

$$\begin{cases} R_{1\mathrm{r}}^a = \arg\max F_{\mathrm{H}-1}(R_{1\mathrm{n}}^a) \\ R_{2\mathrm{r}}^b = \arg\max F_{\mathrm{H}-1}(R_{2\mathrm{n}}^b) \\ R_{3\mathrm{r}}^c = \arg\max F_{\mathrm{H}-1}(R_{3\mathrm{n}}^c) \end{cases} \tag{28}$$

D. INDIVIDUAL FITNESS

For the H^{th} generation, fitness of one individual is related to representative information of other species. The fitness of individual in population can be calculated as follows:

$$\begin{cases} F_H(R_{1\mathrm{n}}^a) = \sum\limits_{tp_{-a}\in \boldsymbol{O}_{-\mathrm{a}}} \rho(tp_{-\mathrm{a}}) C_{DG}^a(f(R_{1\mathrm{n}}^a), \underset{tp_{-\mathrm{a}}}{f}(R_{2\mathrm{r}}^b, R_{3\mathrm{r}}^c)) \\ F_H(R_{2\mathrm{n}}^b) = \sum\limits_{tp_{-\mathrm{b}}\in \boldsymbol{O}_{-\mathrm{b}}} \rho(tp_{-\mathrm{b}}) C_{US}^b(f(R_{2\mathrm{n}}^b), \underset{tp_{-\mathrm{b}}}{f}(R_{1\mathrm{r}}^a, R_{3\mathrm{r}}^c)) \\ F_H(R_{3\mathrm{n}}^c) = \sum\limits_{tp_{-\mathrm{c}}\in \boldsymbol{O}_{-\mathrm{c}}} \rho(tp_{-\mathrm{c}}) C_{DN}(f(R_{3\mathrm{n}}^c), \underset{tp_{-\mathrm{c}}}{f}(R_{1\mathrm{r}}^a, R_{2\mathrm{r}}^b)) \end{cases} \tag{29}$$

E. POPULATION EVOLUTION

The standard genetic operations, selection, crossover, and mutation are used to complete the coevolution process within each population in the H^{th} generation.

F. REPETITION

Repeat steps 1) to 5) until the ecosystem remains stable.

An ecosystem is stable if representatives of various population do not change after several generations. It means the representative combination of these populations is the Bayesian Nash Equilibrium for the multi-lateral incomplete information game. The steady-state fitness of the representatives of various population are as follows:

$$\begin{cases} F(R_{1\mathrm{r}}^a) = \max\limits_{\mathrm{n}}\Big(\sum\limits_{tp_{-\mathrm{a}}\in \boldsymbol{O}_{-\mathrm{a}}} \rho(tp_{-\mathrm{a}}) C_{DG}^a(f(R_{1\mathrm{n}}^a), \underset{tp_{-\mathrm{a}}}{f}(R_{2\mathrm{r}}^b, R_{3\mathrm{r}}^c))\Big) \\ F(R_{2\mathrm{r}}^b) = \max\limits_{\mathrm{n}}\Big(\sum\limits_{tp_{-\mathrm{b}}\in \boldsymbol{O}_{-\mathrm{b}}} \rho(tp_{-\mathrm{b}}) C_{US}^b(f(R_{2\mathrm{n}}^b), \underset{tp_{-\mathrm{b}}}{f}(R_{1\mathrm{r}}^a, R_{3\mathrm{r}}^c))\Big) \\ F(R_{3\mathrm{r}}^c) = \max\limits_{\mathrm{n}}\Big(\sum\limits_{tp_{-\mathrm{c}}\in \boldsymbol{O}_{-\mathrm{c}}} \rho(tp_{-\mathrm{c}}) C_{DN}(f(R_{3\mathrm{n}}^c), \underset{tp_{-\mathrm{c}}}{f}(R_{1\mathrm{r}}^a, R_{2\mathrm{r}}^b))\Big) \end{cases} \tag{30}$$

The overall expected fitness of these species are as follows:

$$\begin{cases} F(R_1) = \sum\limits_{a\in A} \rho(a) F(R_{1\mathrm{r}}^a) \\ F(R_2) = \sum\limits_{b\in B} \rho(b) F(R_{2\mathrm{r}}^b) \\ F(R_3) = \sum\limits_{c=1} \rho(c) F(R_{3\mathrm{r}}^c) \end{cases} \tag{31}$$

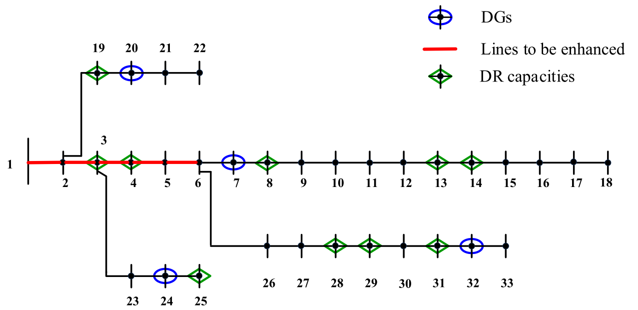

FIGURE 5. The modified IEEE-33 bus distribution system.

TABLE 1. Detailed data of the two DG investors.

No.	Rated Capacity (kW)	Investment Cost (Yuan/kW)	O&M Cost (Yuan/kW·h)	Electricity Price (Yuan/kW·h)
1	90	8000	0.15	0.35
2	100	10000	0.20	0.40

TABLE 2. The specific parameters of wire material.

No.	Cost (Yuan/km)	Impedance (Ω/km)	Maximum Current (A)	Service Life (Year)
1	70000	0.27+j0.4	380	15
2	100000	0.21+j0.4	445	15

V. CASE STUDIES

A. DATA

A modified IEEE 33-bus distribution system, as shown in Fig. 5, is used to verify the proposed method. The peak load is increased to 1.5 times of the original load level. It is assumed that the annual load growth rate is 5% over the next 5-year planning period.

There are two DG investors, with probability of 0.5 for each used in the Harsanyi transformation. Buses 7, 20, 24, and 32 are considered as candidate locations for DGs. DG' subsidy is 0.2 Yuan/kW·h. Detailed data of the two DG investors are shown in Table 1.

One DisCo is considered, with probability of 1 used in the Harsanyi transformation. Existing lines from bus 1 to 2, bus 2 to 3, bus 3 to 4, bus 4 to 5, bus 5 to 6 will be enhanced. Two types of wire material are considered for enhancing lines, and their detailed parameters are shown in Table 2.

There are two DRICSs, with probability of 0.5 for each used in the Harsanyi transformation. Detailed data of the two DRICSs are shown in Table 3. Power purchase price is 0.6 Yuan/kW·h. Consumers at buses 3, 4, 8, 13, 14, 19, 25, 28, 29, and 31 are capable of adjusting loads, with DR capacities ranging from 0% to 50% of respective load levels. Two DR actuation periods are considered for each day: one is the load increasing period including 01:00-7:00 and 22:00-24:00, and the other is the load decreasing period including 09:00-12:00 and 15:00-18:00.

The population size of coevolution algorithm is 100. The crossover probability is 0.9, the mutation probability is 0.05, and the evolutionary generation is 50.

TABLE 3. The specific parameters of the two DRICSs.

No.	DR Capacities Cost (Yuan/kW)	Compensation Income (Yuan/kW·h)	σ
1	14	0.5	0.5
2	21	1	0.7

TABLE 4. The planning results of the proposed method.

Player	Planning Results
DG investor 1	7(270), 20(90), 24(540), 32(270)
DG investor 2	7(300), 20(100), 24(600), 32(200)
DisCo	1-2(2), 2-3(2), 3-4(1), 4-5(0), 5-6(0) 3(20%), 4(20%), 8(30%), 13(10%), 14(20%) 19(20%), 25(50%), 28(10%), 29(20%), 31(20%)

TABLE 5. Expected profit of each player in the two cases.

Player	Case 1(Yuan)	Case 2(Yuan)
DG investor 1	2.1862×10^6	2.1021×10^6
DG investor 2	1.9618×10^6	1.8801×10^6
DisCo	1.9917×10^6	1.9750×10^6
Electricity consumers of DRICS 1	7.5000×10^5	6.2850×10^5
Electricity consumers of DRICS 2	4.6750×10^5	3.8510×10^5

B. STUDY RESULTS

Results of DG investors and the DisCo are shown in Table 4. For DG investor 1, 270kW, 90kW, 540kW, and 270kW DG are built at buses 7, 20, 24, and 32, respectively. For DG investor 2, 300kW, 100kW, 600kW, and 200kW DG are respectively invested at those buses.

For the DisCo, lines from bus 1 to 2, bus 2 to 3, and bus 3 to 4 are enhanced. The DisCo selects type 2 wire material for lines from bus 1 to 2 and bus 2 to 3, and type 1 wire material for the line from bus 3 to 4. DR capacities of buses 3, 4, 14, 19, 29, and 31 are all 20% of their corresponding load levels; DR capacities of buses 8, 13, 28, and 25 are 30%, 10%, 10%, and 50% of their corresponding load levels.

Load adjustment results of consumers are shown in Table A2. Hourly load adjustments of the two DRICSs are different.

C. EFFECTIVENESS VERIFICATION

The following two cases are further studied to verify effectiveness of the proposed method:

Cases 1: Distribution system planning based on the proposed method.

Cases 2: Distribution system planning based on the method of complete information game.

In Case 2, a DG investor, the DisCo and electricity consumers with a DRICS compose a game combination. These players consider the complete information game among themselves in the combination which they belong to. They do not consider the situation of potential combinations including the DG investor's competitors, the DisCo and electricity consumers with other DRICSs. That is, the competitive effects

TABLE 6. Cost and income of DG investors in the two cases in different combinations.

Player	Combination	Case	C_{DG} (Yuan)	$C_{DG,S}$ (Yuan)	$C_{DG,I}$ (Yuan)	$C_{DG,OM}$ (Yuan)	$C_{DG,C}$ (Yuan)
DG investor 1	(1,1,1)	Case 1	2.1862×10^6	2.8698×10^6	1.0935×10^6	1.2299×10^6	1.6398×10^6
		Case 2	2.0180×10^6	2.6490×10^6	1.0094×10^6	1.1353×10^6	1.5137×10^6
	(1,1,2)	Case 1	2.1862×10^6	2.8698×10^6	1.0935×10^6	1.2299×10^6	1.6398×10^6
		Case 2	2.1862×10^6	2.8698×10^6	1.0935×10^6	1.2299×10^6	1.6398×10^6
DG investor 2	(2,1,1)	Case 1	1.9618×10^6	3.3638×10^6	1.4020×10^6	1.6819×10^6	1.6819×10^6
		Case 2	1.7984×10^6	3.0835×10^6	1.2851×10^6	1.5418×10^6	1.5418×10^6
	(2,1,2)	Case 1	1.9618×10^6	3.3638×10^6	1.4020×10^6	1.6819×10^6	1.6819×10^6
		Case 2	1.9618×10^6	3.3638×10^6	1.4020×10^6	1.6819×10^6	1.6819×10^6

TABLE 7. Cost and income of the Disco in the two cases in different combinations.

Combination	Case	C_{DN} (Yuan)	$C_{DN,S}$ (Yuan)	$C_{DN,I}$ (Yuan)	$C_{DN,L}$ (Yuan)	$C_{DN,B1}$ (Yuan)	$C_{DN,B2}$ (Yuan)	$C_{DN,R}$ (Yuan)
(1,1,1)	Case 1	2.1537×10^6	1.1845×10^7	1.7510×10^5	1.1977×10^6	6.1106×10^6	2.1571×10^6	5.1200×10^4
	Case 2	2.0865×10^6	1.1869×10^7	1.7870×10^5	1.2405×10^6	6.2846×10^6	2.0354×10^6	4.2900×10^4
(1,1,2)	Case 1	2.1476×10^6	1.1940×10^7	1.7510×10^5	1.2020×10^6	6.1816×10^6	2.1571×10^6	7.6800×10^4
	Case 2	2.1639×10^6	1.1958×10^7	1.7510×10^5	1.2036×10^6	6.1949×10^6	2.1571×10^6	6.3200×10^4
(2,1,1)	Case 1	1.8357×10^6	1.1845×10^7	1.7510×10^5	1.2086×10^6	6.1014×10^6	2.4734×10^6	5.1200×10^4
	Case 2	1.8157×10^6	1.1870×10^7	1.7510×10^5	1.2204×10^6	6.3239×10^6	2.2921×10^6	4.2900×10^4
(2,1,2)	Case 1	1.8296×10^6	1.1940×10^7	1.7510×10^5	1.2128×10^6	6.1725×10^6	2.4734×10^6	7.6800×10^4
	Case 2	1.8339×10^6	1.1958×10^7	1.7870×10^5	1.2238×10^6	6.1759×10^6	2.4822×10^6	6.3200×10^4

of other players in potential combinations are not considered. On the contrary, in Case 1, these players consider not only the combination which they belong to, but also potential combinations.

Planning results of the DG investors, the DisCo, and consumers in Case 1 are shown in Table 4 and Table A2. For each player, the planning results in different combinations are the same because such planning results is made against all potential combinations. The planning results of Case 2 are shown in Tables A1 and A3-A6. A player's results in different combinations are different, because the player's strategy in one combination is calculated by the game among players in this combination. Specifically, in Case 1, result of DG investor 1 is calculated by the incomplete information game among DG investor 1, the DisCo, consumers of DRICS 1, and consumers of DRICS 2. Therefore, the results of DG investor 1 in combinations (1,1,1) and (1,1,2) are the same. However, in Case 2, the result of DG investor 1 in the combination (1,1,1) is calculated by the game among DG investor 1, the DisCo, and consumers of DRICS 1. The DG investor 1's result in the combination (1,1,2) is calculated by the game among DG investor 1, the DisCo, and consumers of DRICS 2. Therefore, results of DG investor 1 in (1,1,1) and (1,1,2) are different.

The expected profits of different types of stakeholders in these two cases are compared in Table 5. For the sake of comparison, the profit of each player in Case 2 is the mathematical expectation calculated based on its profits in all combinations. As shown in Table 5, these players' expected profits in Case 1 are higher than those in Case 2. The expected profits of DG investor 1 and DG investor 2 in Case 1 increase by 8.4100×10^4 Yuan and 8.1800×10^4 Yuan over those in Case 2. Likewise, the expected profits for consumers of DRICS 1 and DRICS 2 increase by 1.2150×10^5 Yuan and 8.2400×10^4 Yuan, respectively.

The reason of higher profits in Case 1 is that these players could make better decisions by considering all potential combinations. The electricity market makes distribution system planning much more competitive for self-interested independent participants. Thus, by accurately considering these peer competitions in the proposed approach, these players' expected profits in Case 1 are higher than those in Case 2.

For further analysis, the detailed costs and incomes of these players in different combinations are shown in Tables 6-8.

Table 6 shows that, in Case 1, the planning strategies as well as cost and income of DG investors in different combinations are the same. On the contrary, in Case 2, the planning strategies of the two DG investors in these combinations are different because they belong to different combinations. Therefore, their total profits as well as cost and income are different in individual combinations.

For instance, in combination (1,1,1), the electricity sale income of DG investor 1 in Case 1 is 2.2080×10^5 Yuan higher than that of Case 2, while the investment cost is 8.4100×10^4 Yuan higher and the O&M cost is 9.4600×10^4 Yuan higher. In addition, the DG subsidy income is up by 1.2610×10^5 Yuan, and the total income increases by 1.6820×10^5 Yuan. The reason is that, 90kW more DGs are connected at bus 32 in Case 1 than Case 2.

In combination (2,1,1), the electricity sale income of DG investor 2 in Case 1 is 2.8030×10^5 Yuan higher than that of Case 2, while the investment cost is 1.1690×10^5 Yuan higher and the O&M cost is 1.4010×10^5 Yuan higher. Furthermore, the DG subsidy income is up by 1.4010×10^5 Yuan, and the total income increases by 1.6340×10^5 Yuan. The reason is that, 100kW more DGs are connected at bus 24 in Case 1 than Case 2.

Indeed, for combinations (1,1,1) and (2,1,1), as only DRICS 1 is considered in Case 2, the adjustable loads of consumers are less than those in Case 1. Thus, fewer DGs are needed to maintain active and reactive power balance. On the contrary, the two potential DRICSs are both considered in Case 1. This situation leads to an increase in DG requests. Therefore, the total profits of DG investor 1 and 2 in Case 1 are higher than those in Case 2.

For combinations (1,1,2) and (2,1,2), in Case 2, the adjustable loads of DRICS 2 are higher and more DGs capacity can be connected to the network than those in Case 1. However, the DG penetration threshold limits its capacity. As a result, the planning results, cost and income, and the total profits of DG investors 1 and 2 are the same in these two cases.

Overall, expected profits of DG investors are calculated by the above four portfolios, and the two DG investors in Case 1 can obtain higher expected profits than those in Case 2.

Table 7 shows that, in Case 1, the planning strategies of the DisCo in different combinations are the same because such planning strategies is made against all potential combinations. Hence, the line construction cost in different combinations are the same. While other cost and income are different due to difference of DG investors and DRICSs. On the contrary, in Case 2, the planning strategies in these combinations are different because it belongs to different combinations. Therefore, its cost and income are different in individual combinations.

For instance, in combination (1,1,1), the electricity sale income of the DisCo in Case 1 is 2.4000×10^4 Yuan lower than that of Case 2, while the line construction cost is 0.3600×10^4 Yuan lower, the network loss cost is 4.2800×10^4 Yuan lower, and the power purchase expense from the main grid is 1.7400×10^5 Yuan lower. Besides, the power purchase expense from DG investors is 1.2170×10^5 Yuan higher and the signed DR capacity cost is up by 0.8300×10^4 Yuan, while the total profit increases by 6.7200×10^4 Yuan. The reason is that, the lines to be enhanced in Case 1 are shorter than Case 2. In addition, 10% more DR capacities of buses 3, 4, 8, 14, 19 and 29, 10% less DR capacities of bus 13 are signed in Case 1 than those of Case 2.

In combination (1,1,2), the electricity sale income of the DisCo in Case 1 is 1.8000×10^4 Yuan lower than that of Case 2, while the network loss cost is 1.600×10^3 Yuan lower, and the power purchase expense from the main grid is 1.3300×10^4 Yuan lower. Furthermore, the signed DR capacity cost is up by 1.3600×10^4 Yuan, and the total profit decreases by 1.6300×10^4 Yuan. The reason is that, 10% more DR capacities of buses 3, 4, 8, 14, 19 and 29 are signed in Case 1 than those of Case 2, and line investment decisions are unchangeable in the two cases.

In combination (2,1,1), the electricity sale income of the DisCo in Case 1 is 2.5000×10^4 Yuan lower than that of Case 2, while the network loss cost is 1.1800×10^4 Yuan lower, and the power purchase expense from the main grid is 2.2250×10^5 Yuan lower. In addition, the power purchase expense from DG investors is 1.8130×10^5 Yuan higher, while the signed DR capacity cost is up by 8.3000×10^3 Yuan, and the total profit increases by 2.0000×10^4 Yuan. The reason is that, 10% more DR capacities of buses 3, 4, 8, 14, 19 and 29, 10% less DR capacities of bus 28 are signed in Case 1 than those of Case 2. Besides, line investment decisions are unchangeable in the two cases.

In combination (2,1,2), the electricity sale income of the DisCo in Case 1 is 1.8000×10^4 Yuan lower than that of Case 2, while the line construction cost is 0.3600×10^4 Yuan lower, the network loss cost is 1.1000×10^4 Yuan lower, and the power purchase expense from the main grid is 3.400×10^3 Yuan lower. Furthermore, the power purchase expense from DG investors decreases by 8.800×10^3 Yuan, while the signed DR capacity cost increases by 1.3600×10^4 Yuan, and the total profit decreases by 4.300×10^3 Yuan. The reason is that, the lines to be enhanced in Case 1 are shorter than Case 2. In addition, 10% more DR capacities of buses 3, 4, 8, 14, 19 and 29 are signed in Case 1 than those of Case 2.

Indeed, two DRICSs are considered by the DisCo in Case 1 resulting in more signed DR capacities than that of Case 2. In addition, in Case 1, the DisCo can accurately and comprehensively estimate DG connected to system because of peer competition of DG investors. Overall, the DisCo enhances shorter lines and signs more DR capacities in Case 1 than those of Case 2, which makes lower line construction cost, network loss cost and power purchase expense, while higher expected profit.

Table 8 shows that, in the two cases, the cost and income of consumers of two DRICSs in different combinations are the same. Indeed, the profit of electricity consumers is affected by the DisCo' DR strategies. For instance, 10% less DR capacities of buses 13 and 10% more DR capacities of bus 28 are signed in combination (2,1,1) than those of (1,1,1). However, the total DR capacities and adjustable loads are same because of the same load levels for the two buses. Therefore, the profit, cost and income of power consumers of DRICS 1 are the same in these combinations. Moreover, the DisCo' DR strategies are the same in combinations (1,1,2) and (2,1,2), which makes the same mount of adjustable loads. Therefore, the profit, cost and income of electricity consumers of DRICS 2 are the same in these combinations.

For combinations (1,1,1) and (2,1,1), the reduced electricity expense for electricity consumers of DRICS 1 in Case 1 is 6.6300×10^4 Yuan higher than that of Case 2, while the interruptible load compensation income is 5.5200×10^4 Yuan higher, and the total profit increases by 1.2150×10^5 Yuan. For combinations (1,1,2) and (2,1,2), the reduced electricity expense for electricity consumers of DRICS 2 in Case 1 is 3.0900×10^4 Yuan higher than that of Case 2, while the interruptible load compensation income is 5.1500×10^4 Yuan higher, and the total profit increases by 8.2400×10^4 Yuan. The reason is that, the DisCo in Case 1 signs higher DR capacities than that of Case 2, which makes more interruptible load

TABLE 8. Cost and income of electricity consumers in the two cases in different combinations.

Player	Combination	Case	C_{US} (Yuan)	$C_{US,B}$ (Yuan)	$C_{US,C}$ (Yuan)
Electricity Consumers of DRICS 1	(1,1,1)	Case 1	7.5000×10^5	4.0910×10^5	3.4090×10^5
		Case 2	6.2850×10^5	3.4280×10^5	2.8570×10^5
	(2,1,1)	Case 1	7.5000×10^5	4.0910×10^5	3.4090×10^5
		Case 2	6.2850×10^5	3.4280×10^5	2.8570×10^5
Electricity Consumers of DRICS 2	(1,1,2)	Case 1	4.6750×10^5	1.7530×10^5	2.9220×10^5
		Case 2	3.8510×10^5	1.4440×10^5	2.4070×10^5
	(2,1,2)	Case 1	4.6750×10^5	1.7530×10^5	2.9220×10^5
		Case 2	3.8510×10^5	1.4440×10^5	2.4070×10^5

TABLE A1. The planning results of DG investors and the Disco in Case 2.

Player	Combination	Planning Results
DG investor 1	(1,1,1)	7(270), 20(90), 24(540), 32(180)
	(1,1,2)	7(270), 20(90), 24(540), 32(270)
DG investor 2	(2,1,1)	7(300), 20(100), 24(500), 32(200)
	(2,1,2)	7(300), 20(100), 24(600), 32(200)
DisCo	(1,1,1)	1-2(0), 2-3(2), 3-4(2), 4-5(0), 5-6(0) 3(10%), 4(10%), 8(20%), 13(20%), 14(10%), 19(10%), 25(50%), 28(10%), 29(10%), 31(20%)
	(1,1,2)	1-2(2), 2-3(2), 3-4(1), 4-5(0), 5-6(0) 3(10%), 4(10%), 8(20%), 13(10%), 14(10%), 19(10%), 25(50%), 28(10%), 29(10%), 31(20%)
	(2,1,1)	1-2(2), 2-3(2), 3-4(1), 4-5(0), 5-6(0) 3(10%), 4(10%), 8(20%), 13(10%), 14(10%), 19(10%), 25(50%), 28(20%), 29(10%), 31(20%)
	(2,1,2)	1-2(0), 2-3(2), 3-4(2), 4-5(0), 5-6(0) 3(10%), 4(10%), 8(20%), 13(10%), 14(10%), 19(10%), 25(50%), 28(10%), 29(10%), 31(20%)

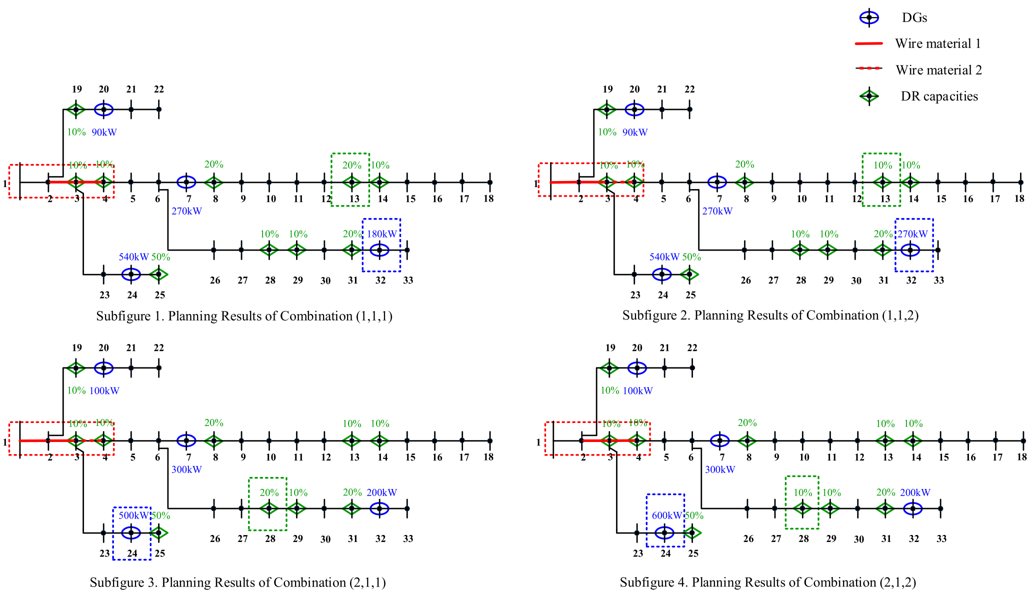

FIGURE A1. The planning results in Case 2.

compensation income and less reduced electricity expense of consumers.

VI. CONCLUSION

In this paper, a distribution system planning approach based on the multi-lateral incomplete information game theory is proposed under the context of competitive market. Profit models of the three types of stakeholders in both supply and demand sides are constructed. The Bayesian Nash equilibrium of the multi-lateral incomplete information game is obtained by the Harsanyi transformation. An improved coevolutionary algorithm is utilized as an effective approach to search for the Bayesian Nash equilibrium. Simulation results show that, compared with complete information game method, the proposed approach has higher expected profits and more accurate planning schemes.

The multi-lateral incomplete information game planning approach can accurately simulate the gaming behavior in

TABLE A2. Demand response results in Case 2.

Player	Time	Adjustable Load(kVA)									
		Bus 3	Bus 4	Bus 8	Bus 13	Bus 14	Bus 19	Bus 25	Bus 28	Bus 29	Bus 31
Electricity Consumer of DRICS 1	1:00	5.26	7.02	17.55	1.75	7.02	5.26	61.42	1.75	7.02	8.77
	2:00	6.48	8.64	21.60	2.16	8.64	6.48	75.60	2.16	6.64	10.80
	3:00	9.18	12.24	30.60	3.06	12.24	9.18	107.10	3.06	12.24	15.30
	4:00	10.80	14.40	36.00	3.60	14.40	10.80	126.00	3.60	14.40	18.00
	5:00	17.45	24.69	36.00	4.88	24.69	17.45	282.96	4.88	24.69	32.38
	6:00	17.88	25.32	72.06	4.99	25.32	17.88	289.16	4.99	25.32	33.20
	7:00	18.33	25.95	73.78	5.11	25.95	18.33	295.36	5.11	25.95	34.03
	9:00	17.67	25.01	75.50	4.94	25.01	17.67	286.06	4.95	25.02	32.79
	10:00	14.24	20.11	72.92	4.05	20.11	14.24	236.51	4.05	20.11	26.34
	11:00	14.45	20.41	59.27	4.10	20.41	14.45	239.60	4.10	20.41	26.74
	12:00	14.03	19.81	60.12	3.99	19.81	14.03	233.41	3.99	19.81	25.95
	15:00	14.03	19.81	58.43	3.99	19.81	14.03	233.41	3.99	19.81	25.95
	16:00	13.50	18.00	45.00	4.50	18.00	13.50	157.50	4.50	18.00	22.50
	17:00	10.80	14.40	36.00	3.60	14.40	10.80	126.00	3.60	14.40	18.00
	18:00	8.10	10.80	27.00	2.70	10.80	8.10	94.50	2.70	10.80	13.50
	22:00	5.26	7.02	17.55	1.75	8.10	5.26	61.42	1.75	7.02	8.77
	23:00	6.48	8.64	21.60	2.16	5.26	6.48	75.60	2.16	8.64	10.80
	24:00	9.18	12.24	30.60	3.06	6.48	9.18	107.10	3.06	12.24	15.30
Electricity Consumer of DRICS 2	1:00	5.26	7.02	17.55	1.75	7.02	5.26	61.42	1.75	7.02	8.77
	2:00	6.48	8.64	21.60	2.16	8.64	6.48	75.60	2.16	9.64	10.80
	3:00	9.18	12.24	30.60	3.06	12.24	9.18	107.10	3.06	12.24	15.30
	4:00	10.80	14.40	36.00	3.60	14.40	10.80	126.00	3.60	14.40	18.00
	5:00	13.15	17.65	47.31	4.34	17.65	13.15	205.14	4.34	17.65	22.24
	6:00	13.43	18.03	48.45	4.34	18.03	13.43	210.46	4.43	18.03	22.72
	7:00	13.71	18.41	49.61	4.52	18.41	13.71	215.80	4.52	18.41	23.20
	9:00	13.29	17.84	47.88	4.38	17.84	13.29	207.79	4.38	17.84	22.48
	10:00	11.07	14.83	39.00	3.66	14.83	11.07	166.25	3.66	14.83	18.64
	11:00	11.20	15.02	39.53	3.70	15.02	11.20	168.78	3.70	15.02	18.88
	12:00	10.93	14.64	38.46	3.61	14.64	10.93	163.72	3.61	14.64	18.41
	15:00	10.93	14.64	38.46	3.61	14.64	10.93	163.72	3.61	14.64	18.41
	16:00	13.50	18.00	45.00	4.50	18.00	13.50	157.50	4.50	18.00	22.50
	17:00	10.80	14.40	36.00	3.60	14.40	10.80	126.00	3.60	14.40	18.00
	18:00	8.10	10.80	27.00	2.70	10.80	8.10	94.50	2.70	10.80	13.50
	22:00	5.26	7.02	17.55	1.75	7.02	5.26	61.42	1.75	7.02	8.77
	23:00	6.48	8.64	21.60	2.16	8.64	6.48	65.60	2.16	8.64	10.80
	24:00	9.18	12.24	30.60	3.06	12.24	9.18	107.10	3.06	12.24	15.30

TABLE A3. Adjustable load in combination (1,1,1) in Case 2.

Player	Time	Adjustable Load(kVA)									
		Bus 3	Bus 4	Bus 8	Bus 13	Bus 14	Bus 19	Bus 25	Bus 28	Bus 29	Bus 31
Electricity Consumer of DRICS 1	1:00	2.63	3.15	11.70	3.51	3.51	2.63	61.42	1.75	3.51	8.77
	2:00	3.24	4.32	14.40	4.32	4.32	3.24	75.60	2.16	4.32	10.80
	3:00	4.59	6.12	20.40	6.12	6.12	4.59	107.10	3.06	6.12	15.30
	4:00	5.40	7.20	24.00	7.20	7.20	5.40	126.00	3.60	7.20	18.00
	5:00	7.90	11.08	45.40	11.08	11.08	7.90	279.34	4.97	11.08	33.26
	6:00	8.10	11.35	46.49	11.35	11.35	8.10	285.44	5.09	11.35	34.10
	7:00	8.29	11.63	47.59	11.63	11.63	8.29	291.55	5.21	11.63	34.94
	9:00	8.00	11.22	45.95	11.22	11.22	8.00	282.39	5.03	11.22	33.68
	10:00	6.50	9.07	38.32	9.07	9.07	6.50	233.60	4.11	9.07	37.11
	11:00	6.59	9.20	38.89	9.20	9.20	6.59	236.65	4.17	9.20	27.52
	12:00	6.40	8.94	37.76	8.94	8.94	6.40	230.56	4.06	8.94	26.71
	15:00	6.40	8.94	37.76	8.94	8.94	6.40	230.56	4.06	8.94	26.71
	16:00	6.75	9.00	30.00	9.00	9.00	6.75	157.50	4.50	9.00	22.50
	17:00	5.40	7.20	24.00	7.20	7.20	5.40	126.00	3.60	7.20	18.00
	18:00	4.05	5.40	18.00	5.40	5.40	4.05	94.50	2.70	5.40	13.50
	22:00	2.63	3.51	11.70	3.51	3.51	2.63	61.42	1.75	3.51	8.77
	23:00	3.24	4.32	14.40	4.32	4.32	3.24	75.60	2.16	4.32	10.80
	24:00	4.59	6.12	20.40	6.12	6.12	4.59	107.10	3.06	6.12	15.30

the opening electricity market. The proposed approach helps market stakeholders focus on the peer competition phenomenon among supply and demand sides. Consequently, they can obtain more accurate planning strategies and higher expected profits than those via complete information game based approaches.

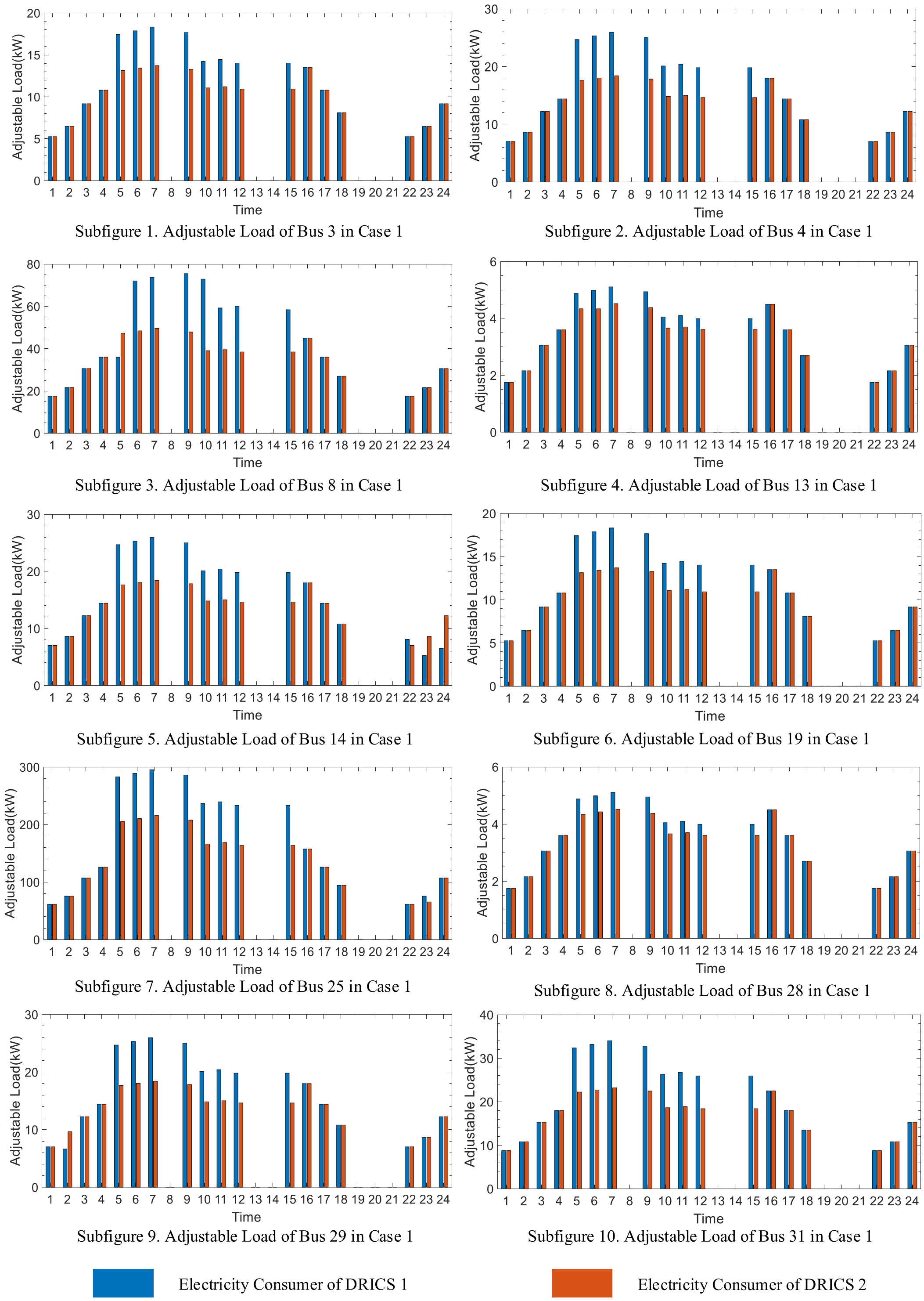

FIGURE A2. The adjustable load results in Case 1.

The proposed approach encourages stakeholders (DG investors, the DisCo, and consumers) to take part in industrial competition. The fairness of self-interested independent participants to pursue individual performance can be guaranteed. Moreover, the competition of stakeholders to invest and construct distribution system can be motivated.

APPENDIX

The planning results in Case 2 are shown in Table A1 and Figure A1. The DR results in Case 1 are shown in Table A2 and Figure A2. The DR results of combinations (1,1,1), (2,1,1), (1,1,2), and (2,1,2) in Case 2 are shown in Table A3 to A6 and Figure A3.

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TABLE A4. Adjustable load in combination (2,1,1) in Case 2.

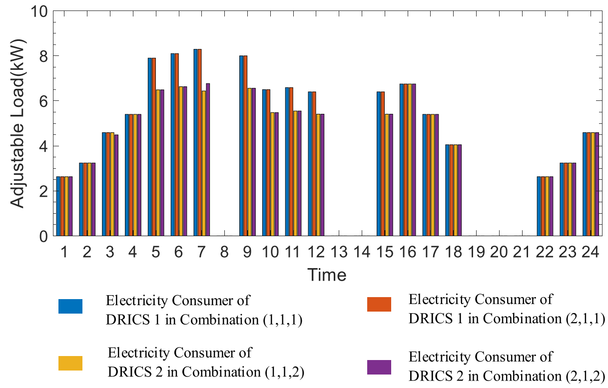
Player	Time	Adjustable Load (kVA)									
		Bus 3	Bus 4	Bus 8	Bus 13	Bus 14	Bus 19	Bus 25	Bus 28	Bus 29	Bus 31
Electricity	1:00	2.63	3.51	11.70	1.75	3.51	2.63	61.42	3.51	3.51	8.77
Consumer of DRICS 2	2:00	3.24	4.32	14.40	2.16	4.32	3.24	75.60	4.23	4.23	10.80
	3:00	4.59	6.12	20.40	3.06	6.12	4.59	107.10	6.12	6.12	15.30
	4:00	5.40	7.20	24.00	3.60	7.20	5.40	126.00	7.20	7.20	18.00
	5:00	7.90	11.08	45.40	4.97	11.08	7.90	279.34	11.08	11.08	33.26
	6:00	8.10	11.35	46.49	5.09	11.35	8.10	285.44	11.35	11.35	34.10
	7:00	8.29	11.63	47.59	5.21	11.63	8.29	291.55	11.63	11.63	34.94
	9:00	8.00	11.22	45.95	5.03	11.22	8.00	282.39	11.22	11.22	33.68
	10:00	6.50	9.07	38.32	4.11	9.07	6.50	233.60	9.07	9.07	27.11
	11:00	6.59	9.20	38.89	4.17	9.20	6.59	236.65	9.20	9.20	27.52
	12:00	6.40	8.94	37.76	4.06	8.94	6.40	230.56	8.94	8.94	26.71
	15:00	6.40	8.94	37.76	4.06	8.94	6.40	230.56	8.94	8.94	26.71
	16:00	6.75	9.00	30.00	4.50	9.00	6.75	157.50	9.00	9.00	22.50
	17:00	5.40	7.20	24.00	3.60	7.20	5.40	126.00	7.20	7.20	18.00
	18:00	4.05	5.40	18.00	2.70	5.40	4.05	94.50	5.40	5.40	13.50
	22:00	2.63	3.51	11.70	1.75	3.51	2.63	61.42	3.51	3.51	8.77
	23:00	3.24	4.32	14.40	2.16	4.32	3.24	75.60	4.32	4.32	10.80
	24:00	4.59	6.12	20.40	3.06	6.12	4.59	107.10	6.12	6.12	15.30

TABLE A5. Adjustable load in combination (1,1,2) in Case 2.

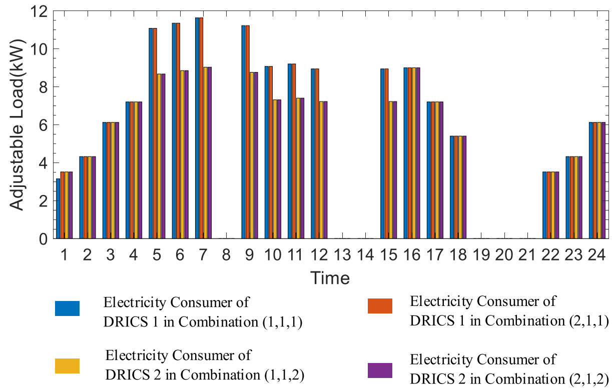
Player	Time	Adjustable Load (kVA)									
		Bus 3	Bus 4	Bus 8	Bus 13	Bus 14	Bus 19	Bus 25	Bus 28	Bus 29	Bus 31
Electricity Consumer of DRICS 1	1:00	2.63	3.51	11.70	1.75	3.51	2.63	61.42	1.75	3.51	8.77
	2:00	3.24	4.32	14.40	2.16	4.32	3.24	75.60	2.16	4.32	10.80
	3:00	4.59	6.12	20.40	3.06	6.12	4.59	107.10	3.06	6.12	15.30
	4:00	5.40	7.20	24.00	3.60	7.20	5.40	126.00	3.60	7.20	18.00
	5:00	6.49	8.67	29.63	4.33	8.67	6.49	199.82	4.33	8.67	21.93
	6:00	6.63	8.85	30.29	4.42	8.82	6.63	205.08	4.42	8.85	22.41
	7:00	6.44	9.03	30.95	4.51	9.03	6.77	210.37	4.51	9.03	22.88
	9:00	6.56	8.76	29.93	4.37	8.76	6.56	202.45	4.37	7.76	22.17
	10:00	5.48	7.31	24.78	3.65	7.31	5.48	161.57	3.65	7.31	18.42
	11:00	5.55	7.40	25.10	3.69	7.40	5.55	164.05	3.69	7.40	18.66
	12:00	5.41	7.22	24.46	3.60	7.22	5.41	159.09	3.60	7.22	18.19
	15:00	5.41	7.22	24.46	3.60	7.22	5.41	159.09	3.60	7.22	18.19
	16:00	6.75	9.00	30.00	4.50	9.00	6.75	157.40	4.50	9.00	22.50
	17:00	5.40	7.20	24.00	3.60	7.20	5.40	126.00	3.60	7.20	18.00
	18:00	4.05	5.40	18.00	2.70	5.40	4.05	94.50	2.70	5.40	13.50
	22:00	2.63	3.51	11.70	1.75	3.51	2.63	61.42	1.75	3.51	8.77
	23:00	3.24	4.32	14.40	2.16	4.32	3.24	75.60	2.16	4.32	10.80
	24:00	4.59	6.12	20.40	3.06	6.12	4.59	107.10	3.06	6.12	15.30

TABLE A6. Adjustable load in combination (2,1,2) in Case 2.

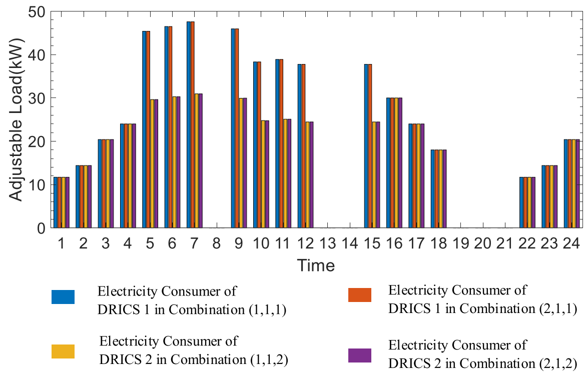
Player	Time	Adjustable Load (kVA)									
		Bus 3	Bus 4	Bus 8	Bus 13	Bus 14	Bus 19	Bus 25	Bus 28	Bus 29	Bus 31
Electricity Consumer of DRICS 2	1:00	2.63	3.51	11.70	1.75	3.51	2.63	61.42	1.75	3.51	8.77
	2:00	3.24	4.32	14.40	2.16	4.32	3.24	75.60	2.16	4.32	10.80
	3:00	4.49	6.12	20.40	3.06	6.12	4.59	107.10	3.06	6.12	15.30
	4:00	5.40	7.20	24.00	3.60	7.20	5.40	126.00	3.60	7.20	18.00
	5:00	6.49	8.67	29.63	4.33	8.67	6.49	199.82	4.33	8.67	31.93
	6:00	6.63	8.85	30.29	4.42	8.85	6.63	205.08	4.42	8.85	22.41
	7:00	6.77	9.03	30.95	4.51	9.03	6.77	210.37	4.51	9.03	22.88
	9:00	6.56	8.76	29.96	4.37	8.76	6.56	202.45	4.37	7.76	22.17
	10:00	5.48	7.31	24.75	3.65	7.31	5.48	161.57	3.65	7.31	18.42
	11:00	5.55	7.40	25.10	3.69	7.40	5.55	164.05	3.69	7.40	18.66
	12:00	5.41	7.22	24.46	3.60	7.22	5.41	159.09	3.60	7.22	18.19
	15:00	5.41	7.22	24.46	3.60	7.22	5.41	159.09	3.60	7.22	18.19
	16:00	6.75	9.00	30.00	4.50	9.00	6.75	157.50	4.50	9.00	22.50
	17:00	5.40	7.20	24.00	4.60	7.20	5.40	126.00	3.60	7.20	18.00
	18:00	4.05	5.40	18.00	2.70	5.40	4.05	94.50	2.70	5.40	13.50
	22:00	2.63	3.51	11.70	1.75	3.51	2.63	61.42	1.75	3.51	8.77
	23:00	3.24	4.32	14.40	2.16	4.32	3.24	75.60	2.16	4.32	10.80
	24:00	4.59	6.12	20.40	3.06	6.12	4.59	107.10	3.06	6.12	15.30



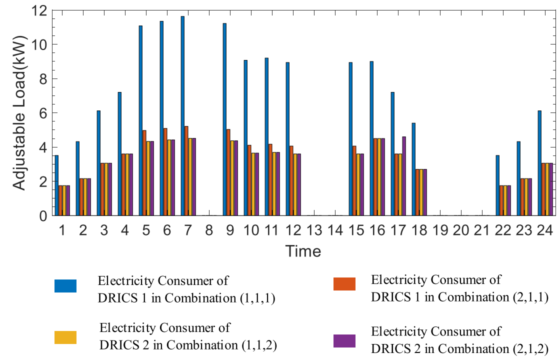
(1) Adjustable Load of bus 3 in Case 2



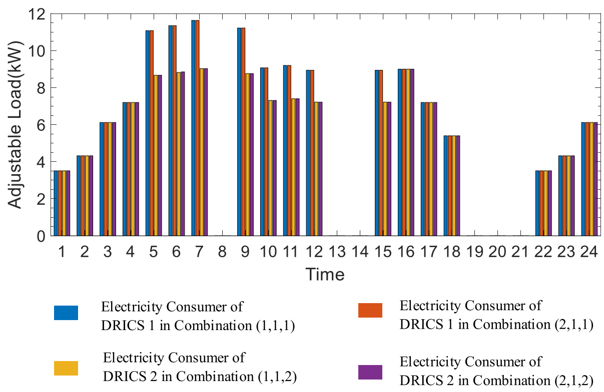
(2) Adjustable Load of bus 4 in Case 2



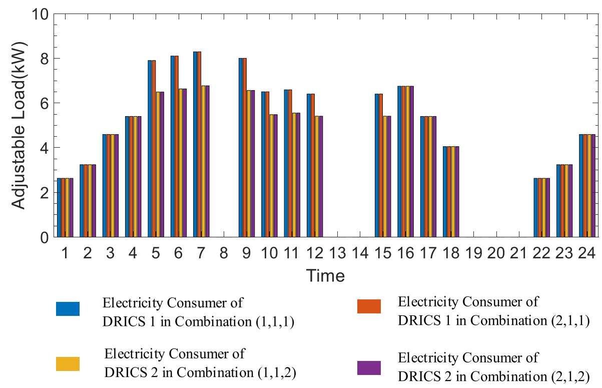
(3) Adjustable Load of bus 8 in Case 2



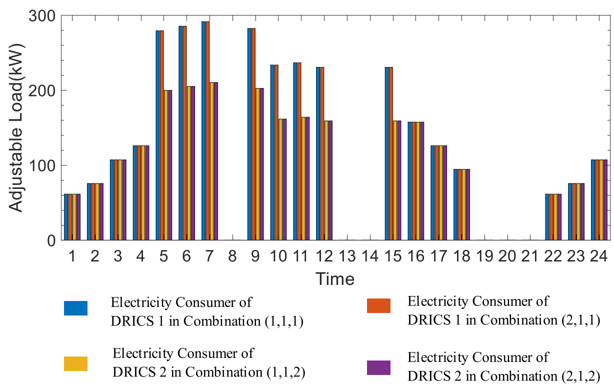
(4) Adjustable Load of bus 13 in Case 2



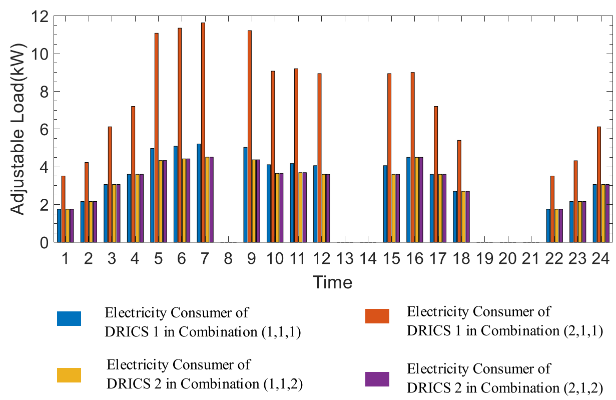
(5) Adjustable Load of bus 14 in Case 2



(6) Adjustable Load of bus 19 in Case 2

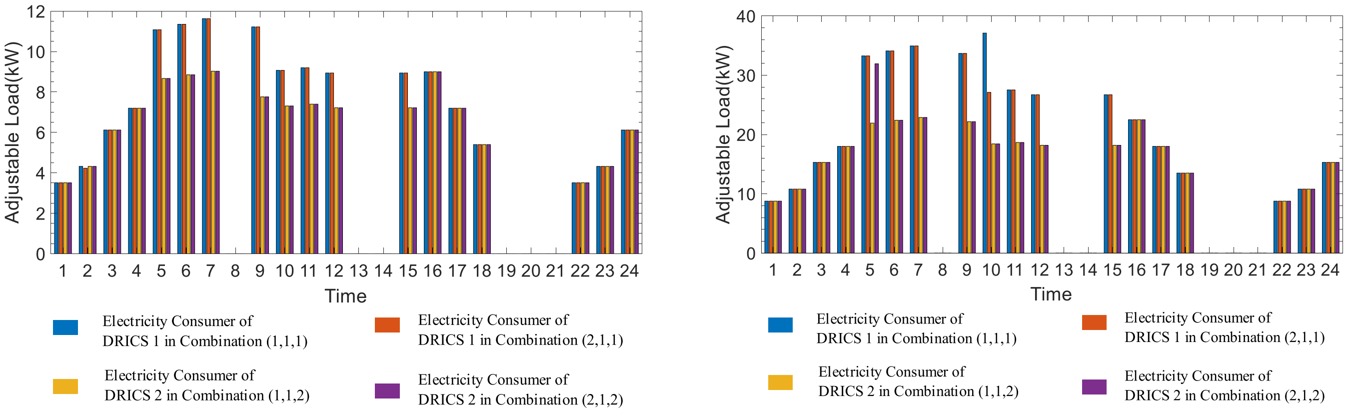


(7) Adjustable Load of bus 25 in Case 2



(8) Adjustable Load of bus 28 in Case 2

FIGURE A3. **The adjustable load results in Case 2.**



(9) Adjustable Load of bus 29 in Case 2

(10) Adjustable Load of bus 31 in Case 2

FIGURE A3. ***(Continued.)*** **The adjustable load results in Case 2.**

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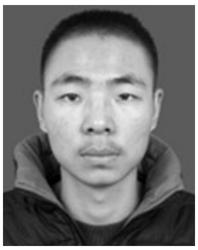

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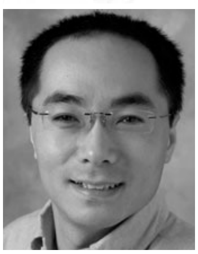

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