Evolutionary Game-theoretic Analysis for Residential Users Considering Integrated Demand Response

Bingtuan Gao, Chen Chen, Yanhui Qin, Xiaofeng Liu, and Zhenyu Zhu

***Abstract*—As an important part of demand side, residential users have the characteristics of imperfect rationality and strong randomness, which are rarely considered in the existing study. Moreover, to effectively improve the energy efficiency, integrated demand response (IDR) is proposed as an effective measure to reduce the local energy supply pressure. This paper focuses on a scenario for IDR programs, in which the intelligent building aggregator (IBA) wants to encourage residential users to participate in IDR according to a proper contract price policy. To analyze how the participation degree tendency evolves over time, an evolutionary game approach is proposed considering residential users' bounded-rationality. A symmetric evolutionary game model and an asymmetric evolutionary game model are established, and the stability of equilibrium points in the above models is proven. Simulation results show that different contract price policies will obviously influence residential users' strategy, and affect the stable equilibrium points of the evolutionary game. The simulation results provide an effective reference for IBA to set proper and effective price incentives.**

***Index Terms*—Contract price, evolutionary game, intelligent community, energy consumption behavior, integrated demand response (IDR).**

I. Introduction

WITH the rapid increase of building energy consumption, there are imminent requirements for the improvement in building energy efficiency [1]. The proliferation of technologies such as integrated energy system (IES) not only enhance the couplings between different energy carries, but also enable customers to participate in integrated demand response (IDR) [2]. By encouraging customers to shift load or convert energy source at a proper time [3], IDR can effectively improve the energy efficiency and system reliability [4].

As an important part of demand side, residential users are regarded as optimization objects in many studies [5]. There have been some IESs with IDR demonstration projects in UK [6] and Germany [7]. These projects are based on a small range of households or several residential buildings. Analyzing different types of users' response behavior and designing reasonable incentive mechanisms are essential for IDR programs. The optimization studies of demand response are generally divided into two categories: one is to minimize load aggregators' operation cost, and the other is to minimize users' energy consumption cost [8]. Mixed integer linear programming (MILP) [9], model predictive control [10], and some intelligent algorithms are commonly used to solve the above optimization issues. Based on price incentive approach, such as real-time pricing (RTP) and time of use price (TOU) [11], game-theoretic methods are employed as optimization solutions in some studies.

As a branch of mathematics, game-theoretic methods have widespread applications in the field of optimization problems, especially strategy choice problems among multiple parties. Games on power demand side mainly include energy consumption games and price games [12]. Cooperative game [13], [14], non-cooperative game [15], [16], and Stackelberg game [17], [18] are usually used to analyze users' consumption behaviors. Non-cooperative game has been wildly used, and with the increase of participants, the existence and proof of Nash equilibrium become difficult to work out. Cooperative game involves the profit disposition through cooperation, and the unfair distribution of profits may lead to union dissolution. Stackelberg game is used when game participants have unequal status, but its equilibrium solution is commonly more complicated. Besides, two-step centralized game [19] and two-level game [20] between power suppliers and consumers have also been applied in the existing literatures. The aforementioned studies all focus on complete information game. For incomplete information scenario, Bayesian game is used to study the residential energy consumption behavior [21], [22].

All of the studies mentioned above assume that the participants have complete rationality. However, energy consumption behavior of residential users in reality is highly random and unpredictable. Subjective freedom and irrationality of

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residential users could also make it difficult for them to fully participate in the IDR. The game approaches adopted by the above studies are not suitable considering users' irrationality. Therefore, it is necessary to propose an optimization approach for bounded-rationality game to analyze this situation. Evolutionary game theory is an efficient solution to animal behavior prediction in resource competition [23], [24], and has been gradually applied to other research domains. In [25], the problem of multi-player evolutionary game with two strategies is considered to analyze how users randomly select different radio access technologies. A two-group and a three-group asymmetric evolutionary games in typical scenarios of electricity market are employed in [26] to analyze how government policies and other factors influence the electricity market. Inspired by the above implementation of evolutionary game approach in different scenarios with irrational users, this paper proposes a way of using evolutionary game to formulate and analyze the participation degree tendency of residential IDR considering the incomplete-information and bounded-rationality. Intelligent community is deployed as an agent to tackle energy trading between users and the smart grid as in [27]. Such an intelligent community consists of several intelligent buildings with certain number of residential users. In order to improve energy efficiency and avoid costly equipment updating, the agent provides incentive contract price policy for residential users who are willing to participate in IDR. For those who are unwilling to participate in IDR, they will pay for their energy consumption with fixed price. Since residential users have different family structures, different users will show different reactions to the same price incentive. This paper reveals the relationship between price policies and residential users' participation degree in IDR projects, and provides an effective reference for IBA to set appropriate price incentives.

The major contributions of this paper can be summarized as follows.

1) A scenario is proposed for IDR programs, in which residential users are irrational, and their energy consumption behaviors are highly random and unpredictable. An evolutionary game based approach is employed to illustrate how the tendency of users' participation degree of IDR evolves over time in the proposed scenario.

2) Symmetric evolutionary game model and asymmetric evolutionary game model are proposed to analyze one type of residential users and different types of residential users, respectively. And the stability of equilibrium points of typical 2×2 evolutionary game is proven mathematically.

The rest of this paper is organized as follows. Symmetric evolutionary game is formulated in Section II to analyze one type of the tendency of residential users' dynamic participation degree in IDR projects. And then a more complex scenario with different types of residential users is formulated and analyzed with asymmetric evolutionary game in Section III. Section IV presents a numerical case study to demonstrate and verify the proposed evolutionary game based analysis of residential IDR, and Section V gives the conclusion.

II. Symmetric Evolutionary Game Modeling Among Group Residential Users

As shown in Fig. 1, a scenario is constructed with a residential community which consists of several intelligent buildings with IESs. Each household in this community has installed smart energy distribution terminals, and all of them meet the IDR technical requirements. IBA is employed to operate the whole system in an economic and efficient way, and collects each household's willingness to participate in IDR project. Residential users can independently decide whether to participate the project or not. Once the system collects each household's decision and calculates the participation proportion, the information will be uploaded to IBA. Based on the participation proportion information, IBA can formulate incentive multi-energy (including cooling, heating and power) prices. For the scenario that residential users' sensitivity to price fluctuations and requirements for environmental comfort are similar to each other, their tendency of participation degree within a period of time can be described as a symmetric evolutionary game.

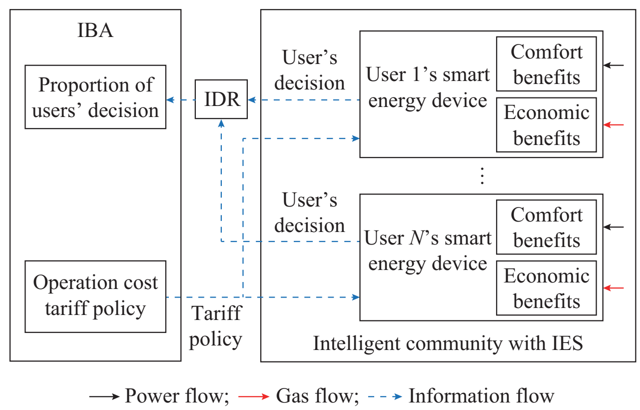

Fig. 1. Structure of symmetric evolutionary game for residential users with similar life style.

Suppose the residential users living in this intelligent community have following strategy set S:

$$S=\{s_1, s_2\} \tag{1}$$

where s_1 represents that the residential user is unwilling to participate in IDR; and s_2 represents that the residential user chooses to participate in IDR.

Users' strategy choices are driven by the payoff. In this paper, the payoff model of residential users consists of economic expenditure and comfort index. In other words, if participating in IDR can achieve higher payoff, the strategy s_2 will be adopted. Economic expenditure depending on whether users participate in IDR is defined as:

$$P_{\mathrm{c}}(s)=\begin{cases}-p_{\mathrm{set}}x_{\mathrm{e}} & s=s_1\\ -p_{\mathrm{con}}x_{\mathrm{e}} & s=s_2\end{cases} \tag{2}$$

where $P_{\mathrm{c}}(s)$ is the users' payoff based on energy price; s is the strategy that the residential user chooses; p_{set} is the fixed price provided by IBA when the residential user chooses strategy s_1; p_{con} is the negotiated energy price provided by IBA when the residential user chooses strategy s_2; and x_{e} is the expected total energy consumption. Since the expected total energy consumption is invariable in this study, without loss of generality, the per unit value of x_e is used. The negotiated price is expressed as:

$$p_{con}=\frac{\kappa_1+\kappa_2+\kappa_3}{\alpha_e+1}+\kappa_4 \tag{3}$$

where κ_1, κ_2, and κ_3 are the electricity, heating, and cooling price parameters decided by the IES cost, respectively; and κ_4 is the adjustment parameter decided by IBA's expected revenue. Suppose the proportion of residential users who choose strategy s_2 is α_e ($0\le\alpha_e\le 1$), thus the proportion of residential users who choose strategy s_1 is $1-\alpha_e$. It can be obtained from (3) that the negotiated price is inversely proportional to the degree of residential users' participation in IDR. That is, the higher the degree of participation, the lower the negotiated price will be.

Participating in IDR has the negative impact on residential users' satisfaction, because the residential users need to adjust their energy consumption behaviors according to IBA's demand. The comfort benefit is an index to describe the actual utility and psychological satisfaction of the residential users when they choose different strategies, which can be represented by the following function [28]:

$$P_s(s)=\begin{cases}\omega_e x_e-\dfrac{a_{ad}}{2}x_e^2-b_{ad}\left(e^{-\alpha_e}+\delta_r\right) & s=s_1\\ -\left[\omega_e x_e-\dfrac{a_{ad}}{2}x_e^2-b_{ad}\left(e^{-\alpha_e}+\delta_r\right)\right] & s=s_2\end{cases} \tag{4}$$

where ω_e is a utility return coefficient; a_{ad} and b_{ad} are the adjustment coefficients; and δ_r is a random variable of environmental impact.

The total payoff of participants of this evolutionary game is as follows:

$$P_\Sigma=P_c+P_s \tag{5}$$

Suppose the residential users living in an intelligent building with identical characteristics are divided into two groups: group A and group A'. Their payoff matrix of symmetric game is shown in Table I. There are 8 payoffs in this 2×2 evolutionary game, which can be represented as:

$$P_{\Sigma 1}=P_c\left(s_1\right)+P_{s121} \tag{6}$$

$$P_{\Sigma 2}=P_c\left(s_1\right)+P_{s111} \tag{7}$$

$$P_{\Sigma 3}=P_c\left(s_2\right)+P_{s222} \tag{8}$$

$$P_{\Sigma 4}=P_c\left(s_2\right)+P_{s212} \tag{9}$$

$$P_{\Sigma 5}=P_c\left(s_2\right)+P_{s212} \tag{10}$$

$$P_{\Sigma 6}=P_c\left(s_1\right)+P_{s111} \tag{11}$$

$$P_{\Sigma 7}=P_c\left(s_2\right)+P_{s222} \tag{12}$$

$$P_{\Sigma 8}=P_c\left(s_1\right)+P_{s121} \tag{13}$$

where P_{s121} is the comfort benefit of group A when group A chooses strategy s_1 and group A' chooses strategy s_2; $P_{\Sigma 1}$ is the total payoff of group A; P_{s111} is the comfort benefit of group A when group A chooses strategy s_1 and group A' chooses strategy s_1; $P_{\Sigma 2}$ is the total payoff of group A; P_{s222} is the comfort benefit of group A when group A chooses strategy s_2 and group A' chooses strategy s_2; $P_{\Sigma 3}$ is the total payoff of group A; P_{s212} is the comfort benefit of group A when group A chooses strategy s_2 and group A' chooses strategy s_1; $P_{\Sigma 4}$ is the total payoffs of group A; and $P_{\Sigma 5}$,$P_{\Sigma 6}$,$P_{\Sigma 7}$, and $P_{\Sigma 8}$ are the total payoffs of group A' in the above four cases. Because group A and group A' are symmetrical, $P_{\Sigma 1}=P_{\Sigma 8}$, $P_{\Sigma 2}=P_{\Sigma 6}$, $P_{\Sigma 3}=P_{\Sigma 7}$, and $P_{\Sigma 4}=P_{\Sigma 5}$.

TABLE I
GAME MATRIX OF SYMMETRIC EVOLUTIONARY GAME OF RESIDENTIAL USERS

Strategy	Element of game matrix	
	Strategy $s_2(\alpha_e)$ (user group A')	Strategy $s_1(1-\alpha_e)$ (user group A')
Strategy $s_1(1-\alpha_e)$ (user group A)	$P_{\Sigma 1}$, $P_{\Sigma 5}$	$P_{\Sigma 2}$, $P_{\Sigma 6}$
Strategy $s_2(\alpha_e)$ (user group A)	$P_{\Sigma 3}$, $P_{\Sigma 7}$	$P_{\Sigma 4}$, $P_{\Sigma 8}$

For users who choose not to participate in IDR, their payoff expectation can be calculated as:

$$\begin{aligned}E\left(s_1\right)=\alpha_e P_{\Sigma 1}+\left(1-\alpha_e\right)P_{\Sigma 2}=\alpha_e\left(P_c\left(s_1\right)+P_{s121}\right)+\\ \left(1-\alpha_e\right)\left(P_c\left(s_1\right)+P_{s111}\right)\end{aligned} \tag{14}$$

For users who choose to participate in IDR, their payoff expectation can be calculated as:

$$\begin{aligned}E\left(s_2\right)=\alpha_e P_{\Sigma 3}+\left(1-\alpha_e\right)P_{\Sigma 4}=\alpha_e\left(P_c\left(s_2\right)+P_{s222}\right)+\\ \left(1-\alpha_e\right)\left(P_c\left(s_2\right)+P_{s212}\right)\end{aligned} \tag{15}$$

The average payoff expectation of all users can be expressed as:

$$E(s)=\left(1-\alpha_e\right)E\left(s_1\right)+\alpha_e E\left(s_2\right) \tag{16}$$

The replicator dynamics equation of residential users who choose to participate in IDR can be mathematically expressed as follows:

$$\begin{aligned}F\left(\alpha_e\right)=\frac{d\alpha_e}{dt}=\alpha_e\left(E\left(s_2\right)-E(s)\right)=\\ \alpha_e\left[E\left(s_2\right)-\left(1-\alpha_e\right)E\left(s_1\right)-\alpha_e E\left(s_2\right)\right]=\\ \alpha_e\left(1-\alpha_e\right)\left(E\left(s_2\right)-E\left(s_1\right)\right)=\\ \alpha_e\left(1-\alpha_e\right)\left[\alpha_e\left(P_{\Sigma 2}+P_{\Sigma 3}-P_{\Sigma 1}-P_{\Sigma 4}\right)+P_{\Sigma 4}-P_{\Sigma 2}\right]\end{aligned} \tag{17}$$

Assuming $F(\alpha_e)=0$, all the equilibrium points of the replicator dynamics equation can be resolved as follows:

$$\alpha_{e1}=0 \tag{18}$$

$$\alpha_{e2}=1 \tag{19}$$

$$\alpha_{e3}=\frac{P_{\Sigma 2}-P_{\Sigma 4}}{P_{\Sigma 2}+P_{\Sigma 3}-P_{\Sigma 1}-P_{\Sigma 4}} \tag{20}$$

In evolutionary game, points corresponding to the solution of the replicator dynamics equation are not always stable equilibrium points. Thus, the stability of equilibrium points needs to be analyzed.

Theorem 1: consider a general 2×2 evolutionary game, if the solution of replicator dynamics equation satisfies the following formula, it has a corresponding stable equilibrium point:

$$\begin{cases}\det(\boldsymbol{J})>0\\ \operatorname{tr}(\boldsymbol{J})<0\end{cases} \tag{21}$$

where $\boldsymbol{J}$ is a 2×2 Jacobian matrix corresponding to the replicator dynamic equations; $\det(\boldsymbol{J})$ is the determinant of the Jacobian matrix; and $\operatorname{tr}(\boldsymbol{J})$ is the trace of the Jacobian matrix.

The proof of theorem 1 is given in Appendix A. The essence of theorem 1 is to determine the stability of equilibrium point of the evolutionary game by checking the local stability criterion of Jacobian matrix in the dynamic system. When there is only one dynamic (9) for symmetric evolutionary game, the stability analysis criterion of equilibrium point based on Jacobian matrix transfers to:

$$F'\left(\alpha_{\mathrm{e}}\right)<0 \tag{22}$$

Plug (17) into (22), (22) is expressed as:

$$\begin{aligned}F'\left(\alpha_{\mathrm{e}}\right)=&-3\left(P_{\Sigma 2}+P_{\Sigma 3}-P_{\Sigma 1}-P_{\Sigma 4}\right)\alpha_{\mathrm{e}}^{2}+\\&2\left(2P_{\Sigma 2}+P_{\Sigma 3}-P_{\Sigma 1}-2P_{\Sigma 4}\right)\alpha_{\mathrm{e}}+P_{\Sigma 4}-P_{\Sigma 2}+\\&\left(\alpha_{\mathrm{e}}-\alpha_{\mathrm{e}}^{2}\right)\left(P'_{\mathrm{con}}+P'_{\mathrm{s}212}-P'_{\mathrm{s}111}\right)<0\end{aligned} \tag{23}$$

where P'_{con}, $P'_{\mathrm{s}212}$, and $P'_{\mathrm{s}111}$ are the derivatives of P_{con}, $P_{\mathrm{s}212}$, and $P_{\mathrm{s}111}$, respectively.

According to (23), the stability of three equilibrium points will be affected by the payoffs functioned with incentive pricing indeed. The stable equilibrium point of the evolutionary game corresponds to the final proportion sharing the same strategy. As a result, the evolutionary result with different incentive pricing policies formulated by IBA can be analyzed.

III. Asymmetric Evolutionary Game Modeling Among Group Residential Users

In reality, different households may have various family structures and lifestyles. It's necessary to consider asymmetric evolutionary game model for different kinds of residential users. For different categories of residential groups, their energy consumption behaviors will show diverse characteristics. For example, families with young people may have few loads (including electricity, heating and cooling loads) at daytime and care more about the comfort degree, while families with the elders and children may have much more loads at daytime and are more sensitive to the price fluctuation.

The negotiated energy price of asymmetric evolutionary game is defined as:

$$p_{\mathrm{con}}=\frac{a\kappa_1+b\kappa_2+c\kappa_3}{\alpha_{\mathrm{e}}+1}+\kappa_4 \tag{24}$$

where a, b, and c are residential users' sensitivity parameters to electricity, heating, and cooling prices, respectively. Different categories of residential users have diverse energy demands, so their sensitivity parameters are different.

As shown in Fig. 2, the asymmetric evolutionary game considered in this section increases the residential categories compared with the symmetric case, where the residential users are divided into M categories.

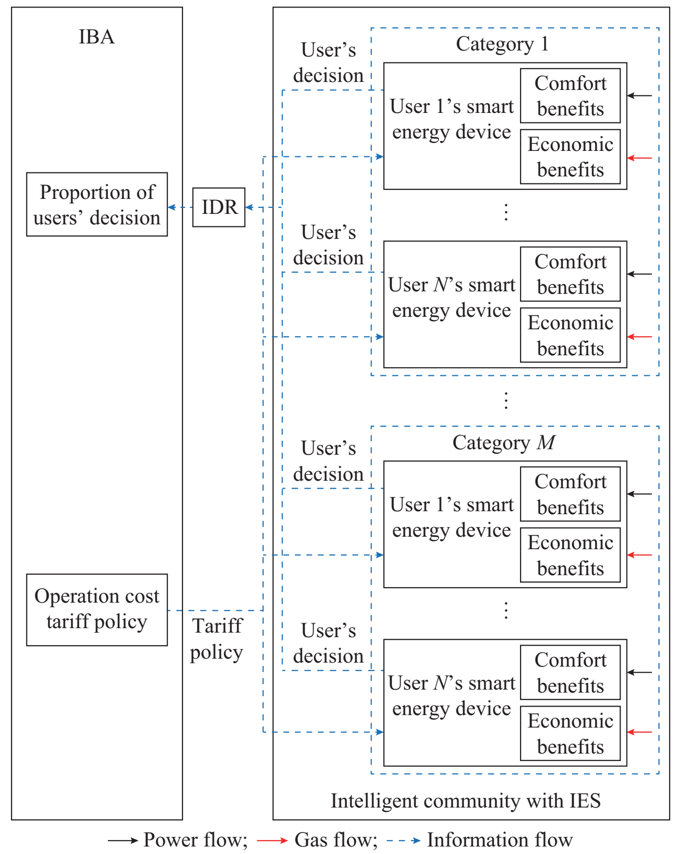

Fig. 2. Structure of asymmetric evolutionary game for residential users with different lifestyles.

The residential users' strategy set for the asymmetric evolutionary game is the same as in Section II. The payoff of group i who chooses to participate in IDR is $P_{i\mathrm{T}j}$, and the payoff of group i who does not participate in IDR is $P_{i\mathrm{F}j}$, $i\in\{1,2,\ldots,M\}$, $j\in\{1,2,\ldots,n\}$, $n=2^M$. The payoffs in different strategies can be illustrated in Fig. 3. The payoff matrix $\boldsymbol{D}_i$ of group i is given as:

$$\boldsymbol{D}_i=\begin{bmatrix}P_{i\mathrm{T}1} & P_{i\mathrm{T}2} & \cdots & P_{i\mathrm{T}n}\\ P_{i\mathrm{F}1} & P_{i\mathrm{F}2} & \cdots & P_{i\mathrm{F}n}\end{bmatrix} \tag{25}$$

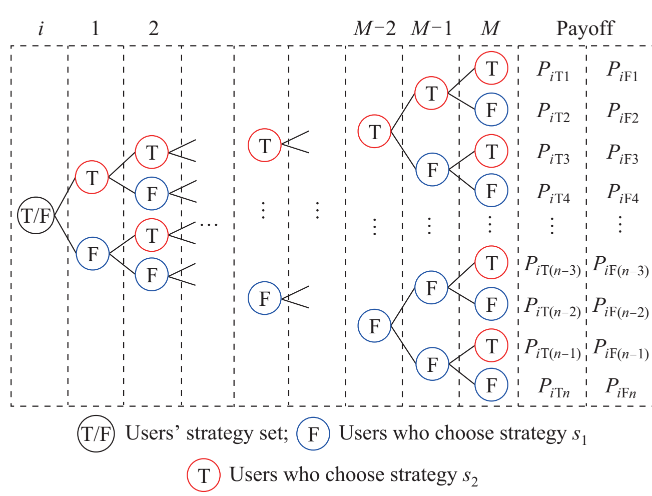

Fig. 3. Users' payoffs in different strategies of asymmetric evolutionary game.

For group i, suppose that the proportion of residential users sharing the strategy with participation in the IDR is β_{ei} $(0 \le \beta_{ei} \le 1)$, thus the proportion of the rest residential users is $1-\beta_{ei}$. Then, the payoff expectation of group i who chooses to participate in IDR is calculated as:

$$E_{i1} = \beta_{e1}\beta_{e2}\cdots\beta_{e(i-1)}\beta_{e(i+1)}\cdots\beta_{e(M-1)}\beta_{eM}P_{iT1} + \beta_{e1}\beta_{e2}\cdots\beta_{e(i-1)}\beta_{e(i+1)}\cdots\beta_{e(M-1)}\left(1-\beta_{eM}\right)P_{iT2} + \cdots + \left(1-\beta_{e1}\right)\left(1-\beta_{e2}\right)\cdots\left(1-\beta_{e(i-1)}\right)\left(1-\beta_{e(i+1)}\right)\cdots\left(1-\beta_{e(M-1)}\right)\left(1-\beta_{eM}\right)P_{iTn} \tag{26}$$

And the payoff expectation of group i who chooses not to participate in IDR is calculate as:

$$E_{i2} = \beta_{e1}\beta_{e2}\cdots\beta_{e(i-1)}\beta_{e(i+1)}\cdots\beta_{e(M-1)}\beta_{eM}P_{iF1} + \beta_{e1}\beta_{e2}\cdots\beta_{e(i-1)}\beta_{e(i+1)}\cdots\beta_{e(M-1)}\left(1-\beta_{eM}\right)P_{iF2} + \cdots + \left(1-\beta_{e1}\right)\left(1-\beta_{e2}\right)\cdots\left(1-\beta_{e(i-1)}\right)\left(1-\beta_{e(i+1)}\right)\cdots\left(1-\beta_{e(M-1)}\right)\left(1-\beta_{eM}\right)P_{iFn} \tag{27}$$

The average payoff expectation of group i is calculated as:

$$E_i = \left(1-\beta_{ei}\right)E_{i2} + \beta_{ei}E_{i1} \tag{28}$$

Replicator dynamic equation of group i who is willing to participate in IDR can be mathematically expressed as follows:

$$F(i) = \beta_{ei}\left(E_{i1} - E_i\right) = \dot{\beta}_{ei} \tag{29}$$

Solution of the replicator dynamics equation and stability analysis of the evolutionary equilibrium points are similar to the symmetric evolutionary game presented in the last section.

Users' energy consumption behavior may be affected by a short-term emergency situation. Uncertainty or randomness may timely influence residential users' final strategy choice. Therefore, the residential uses' random strategy needs to be considered in the model. According to the established replicator dynamic equations, the dynamic proportion β_{ei} is changing with time:

$$X_i = \beta_{ei}(t) \tag{30}$$

where X_i is the proportion of residential users considering their random behaviors.

Assuming that some residential users in group i change their strategies at time T for some random reasons, and the changed value of proportion is $r_{i,T}$. The new proportion at time T is expressed as:

$$\begin{cases} X_{i,T} = X_{i,T-1} - r_{i,T-1} \\ 0 \le r_{i,T-1} \le X_{i,T-1} \end{cases} \tag{31}$$

Then, substituting the disturbed $X_{i,T}$ as β_{ei} in the evolution process, the new proportion of at time $T+1$ can be calculated.

IV. Case Study

In this section, simulation results of the symmetric evolutionary model and the asymmetric evolutionary model are presented. To encourage residential users, IBA has established the following tariff policies.

Tariff policy 1: if the residential user does not participate in IDR, the fixed electricity price is p_{eset} = 0.79 RMB/kWh [29], the fixed heating price is p_{hset} = 0.40 RMB/kWh [30] and the fixed colding price is p_{cset} = 0.50 RMB/kWh. If the residential user participates in IDR, the contract electricity price is set as $p_{econ} = 0.79/(0.45\alpha_e + 1)$, the contract heating price is set as $p_{hcon} = 0.40/(0.45\alpha_e + 1)$, and the contract cooling price is set as $p_{ccon} = 0.50/(0.45\alpha_e + 1)$. It also stipulates that the minimum multi-price $p_{econ} + p_{hcon} + p_{ccon}$ should be higher than 1.4 RMB/kWh.

Tariff policy 2: if the residential user participates in IDR, the contract electricity price is set as $p_{econ} = 0.70/(0.45\alpha_e + 1)$, the contract heating price is set as $p_{hcon} = 0.35/(0.45\alpha_e + 1)$ and the contract cooling price is set as $p_{ccon} = 0.44/(0.45\alpha_e + 1)$. Minimum multi-price $p_{econ} + p_{hcon} + p_{ccon}$ should be higher than 1.4 RMB/kWh.

Tariff policy 3: if the residential user participates in IDR, the contract electricity price is set as $p_{econ} = 0.65/(0.45\alpha_e + 1)$, the contract heating price is set as $p_{hcon} = 0.32/(0.45\alpha_e + 1)$ and the contract cooling price is set as $p_{ccon} = 0.40/(0.45\alpha_e + 1)$. Minimum multi-price $p_{econ} + p_{hcon} + p_{ccon}$ should be higher than 1.32 RMB/kWh.

A. Symmetric Evolutionary Game

To simulate the symmetric evolutionary game, only one kind of residential users are supposed to live in the intelligent community in this part. Comfort benefit index of residential users is expressed as $p_{sA} = 0.8 + 1.5(e^{-x} + \delta_r)$, where $\delta_r \in (0,1)$. All 100 households of this intelligent community meet the requirements of the hardware and software for IDR. In the initial stage of IDR implementation, only 8 residential users are willing to participate in IDR, and residential users' strategy adjustment cycle is 7 days. The simulation results for three tariff policies are shown in Fig. 4.

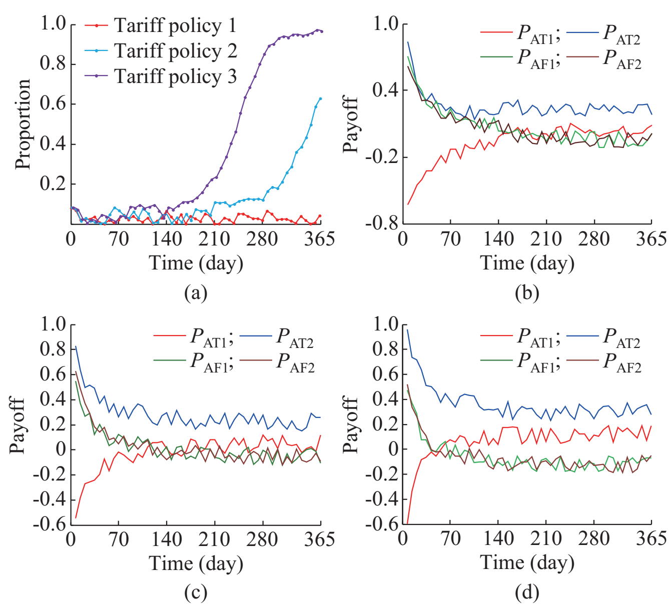

Fig. 4. Simulation results of symmetric evolutionary game. (a) Tendency of participating users' proportion for three tariff policies. (b) Tendency of residential users' payoffs for tariff policy 1. (c) Tendency of residential users' payoffs for tariff policy 2. (d) Tendency of residential users' payoffs for tariff policy 3.

Figure 4(a) shows the proportion of residential users who choose to participate in IDR for three different tariff policies. Figure 4(b)-(d) shows the tendency of their payoff fluctuations for three tariff policies, respectively. The payoff of who chooses to participate in IDR is P_{ATj}, and the payoff of who does not participate in IDR is P_{AFj}. Figure 4(a) shows that for tariff policy 1, the participation of residential users is very low in one year. The overall tendency shows that most of the residential users are finally not willing to participate in IDR. Figure 4(b) shows that if residential users participating in IDR, they will obtain less than those who do not participate in. If IBA wants more residential users to participate in IDR, tariff policy 1 will not be adopted because the revenue of price stimuli is insufficient.

In order to encourage residential users, tariff policy 2 is taken to increase the economic benefits. Figure 4(a) shows that for tariff policy 2, the participation of residential users is growing slowly. But after a year, much more residential users choose to participate in IDR than for tariff policy 1. It can be seen from Fig. 4(b) that the profit of participating in IDR is growing slowly. Thus, the overall tendency shows that residential users finally are willing to participate in IDR, but it will take a long period of time.

If IBA intends to improve the participation of IDR in a short time, tariff policy 3 should be adopted. Figure 4(c) shows that residential users who participate in IDR are able to gain more benefits than those who do not participate in IDR. Therefore, residential users' profitability makes them choose a strategy which can bring greater benefits.

B. Asymmetric Evolutionary Game

To simulate asymmetric evolutionary game, residential users living in the intelligent community are divided into two categories. One category is the family type-A with low-schedulability, which only consists of young workers. The other is family type-B with high sensitivity of price fluctuation and high schedulability, which consists of young workers, elder, and children. Family type-A cares more about comfort degree and is more sensitive to the heat price fluctuation, while family type-B cares more about the financial cost and is more sensitive to the cooling price fluctuation. Suppose there are 25 type-A users and 75 type-B users living in this intelligent community. In the initial stage of IDR implementation, only 2 type-A users and 8 type-B users are willing to participate in IDR, and users' strategy adjustment cycle is 7 days.

At first, IBA adopts tariff policy 1. Sensitivity parameters of the negotiated price are set as $a_A = 1$, $b_A = 1.2$, $c_A = 0.8$ and $a_B = 1.2$, $b_B = 0.8$, $c_B = 1.2$ for type-A and type-B users, respectively. Comfort benefits for type-A users is set as: $p_{sA} = 0.8 + 1.5(e^{-x} + \delta_r)$, while the comfort benefit for type-B users is set as: $p_{sB} = 0.9 + 1.05(e^{-x} + \delta_r)$. The simulation results are shown in Fig. 5.

Figure 5(a) shows that the participation degrees of two types of residential users are significant sluggish in one year: type-A users rarely participate in IDR, while type-B users' participation growth is slow. It can be seen from Fig. 5(b) and Fig. 5(c) that, the payoff of type-A users who participate in IDR is less than the payoff of those who do not participate in IDR. Thus, type-A users are unwilling to participate in IDR. Although some type-B users are willing to participate in IDR to get certain benefits, their payoffs gradually decrease to zero over time.

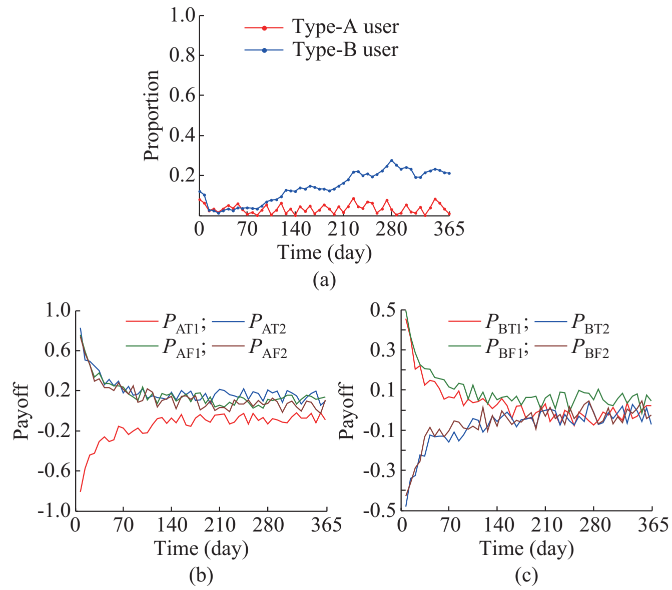

Fig. 5. Simulation results of tariff policy 1 in asymmetrical evolutionary game. (a) Tendency of participating users' proportion for tariff policy 1. (b) Tendency of type-A users' payoffs for tariff policy 1. (c) Tendency of type-B users' payoffs for tariff policy 1.

In this case, although residential users may have the tendency to participate in IDR, the growth is slow. The phase diagram for tariff policy 1 is shown in Fig. 6. Red arrows are added manually to point out the evolutionary tendency. It can be seen that the stable equilibrium point of the game is located at (0, 0). If IBA intends to change the stable equilibrium point to (1, 1), the new tariff policy should be provided to increase the residential users' payoff.

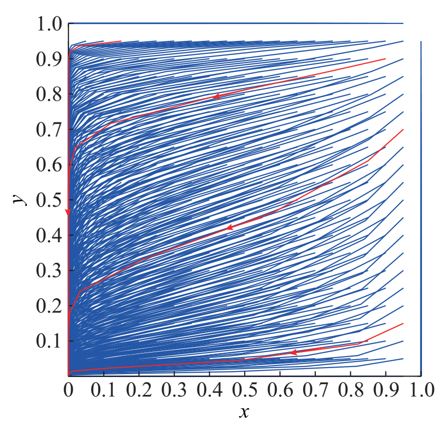

Fig. 6. Phase diagram of asymmetric evolutionary game under tariff policy 1.

Tariff policy 2 is provided to encourage more residential users to participate in IDR, the simulation results are shown in Fig. 7. Figure 7(a) shows that the proportion of participation in IDR for type-B users reaches a high degree soon, while type-A users' participation degree grows slowly at the beginning. After 1 year, type-A and type-B users are mostly willing to participate in IDR. Figure 7(b) and (c) shows payoff variations of two types of residential users in a year. Because type-A users have high demand for environment comfort, type-A users are still unwilling to sacrifice comfort for economic benefits in the first 210 days.

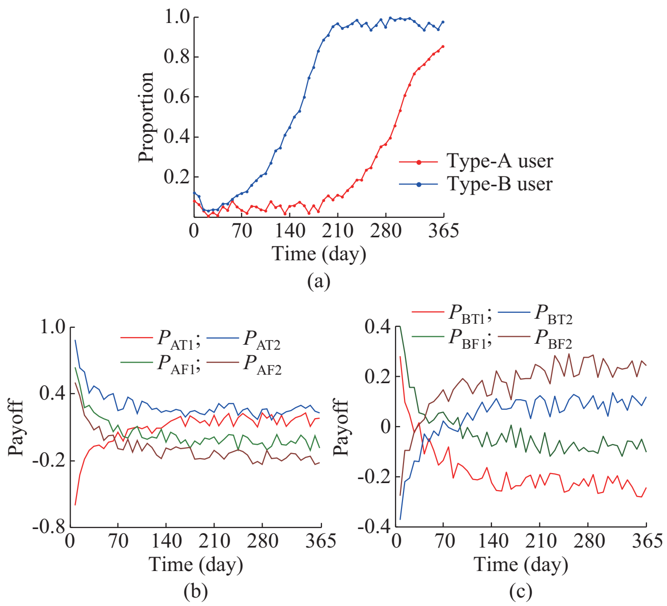

Fig. 7. Simulation results of tariff policy 2 in asymmetric evolutionary game. (a) Tendency of participating users' proportion for tariff policy 2. (b) Tendency of type-A users' payoffs for tariff policy 2. (c) Tendency of type-B users' payoffs for tariff policy 2.

If IBA hopes both type-A and type-B users have high participation degrees of IDR in a shorter time, tariff policy 3 can be adopted. The simulation results are shown in Fig. 8.

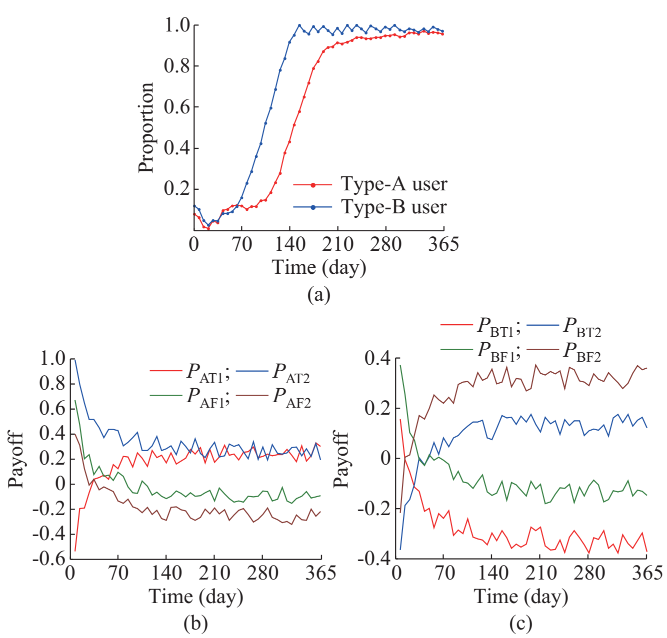

Fig. 8. Simulation results of tariff policy 3 in asymmetrical evolutionary game. (a) Tendency of participating users' proportion for tariff policy 3. (b) Tendency of type-A users' payoffs for tariff policy 3. (c) Tendency of type-B users' payoffs for tariff policy 3.

Figure 8(a) shows that if IBA provides tariff policy 3, type-A and type-B users gradually reaches 45% and 90% participation degrees in the first 140 days, respectively. Figure 8(b) and (c) shows that for both two types of residential users, when the IBA provides great economic benefits, the residential users will choose a strategy that can bring greater benefits in a short time by considering the profitability. Figure 9 shows that the stable equilibrium point of policy 3 is (1, 1).

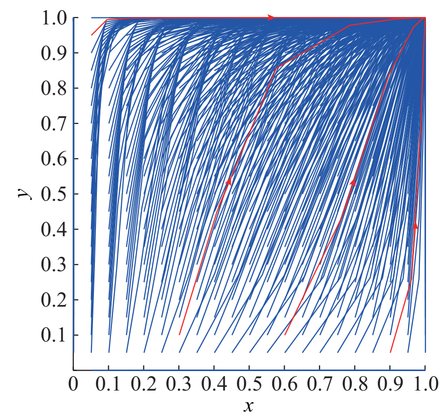

Fig. 9. Phase diagram of asymmetric evolutionary game for tariff policy 3.

It can be seen that from the above simulation results, although the external environment and residential users' nonrational choice will cause some random fluctuation, the established evolutionary game models are able to resist these fluctuations and finally approach to a stable state. Based on the above three cases of symmetric evolutionary games and asymmetric evolutionary games, it can be seen that the stronger the price stimulation is, the shorter the time is for residential users to increase their participation degrees of IDR. Therefore, IBA needs to consider the balance between its own profit and residential users' participation degree of IDR. If 50% of the residential users' participation in the short term can meet the scheduling requirements, tariff policy 2 will be adopted. If 100% of the residential users' participation can meet the scheduling requirements, tariff policy 3 will be adopted.

Compared residential users in the symmetric evolutionary game with type-A users in the asymmetric evolutionary game, the only difference between them is the sensitive parameters of the negotiated price. With higher sensitive parameters to specific group of residential users for the same price policy, the group of residential users are strongly willing to participate in IDR. Therefore, if IBA can make a detailed investigation about residential users' energy using behaviors and analyze which kind of price policies they value most, less price stimulation will achieve better participation degree.

V. Conclusion

Considering practical imperfect rationality and strong randomness characteristics during the process that residential users participate in IDR projects, an evolutionary game based approach is proposed to study how the users' participation tendency of IDR evolves over time. Symmetric and asymmetric evolutionary game models are established for different scenarios of IDR. Analysis on replicator dynamics of the evolutionary game shows that the existence of evolutionary stable strategy or stable equilibrium is highly dependable on payoff parameters which can be managed by IBA. Simulation results on symmetric and asymmetric evolutionary games both with three types of contract price policies show that different contract price policies can affect residential participation degree tendency of IDR significantly and can change the stable equilibrium points of the evolutionary game. It demonstrates that it is feasible to use the proposed evolutionary game based approach to analyze and formulate appropriate contract pricing mechanism for IBA or similar operators on demand side.

The proposed approach can be extended to other scenarios, such as the residential users' participation degree tendency of demand response at different time during one day. It needs to be pointed out that the proposed approach is only applicable for the scenario where the strategy set only has two choices. The future work will be focused on multi-party multi-strategy asymmetric evolutionary game among different types of residential users.

APPENDIX A

Considering a 2×2 evolutionary game in Table AI, where y^s is the proportion choosing strategy 1 in group A^s; $1-y^s$ is the proportion with strategy 2 in group A^s; x^s is the proportion choosing strategy 1 in group B^s; $1-x^s$ is the proportion with strategy 2 in group B^s; a^s, b^s, c^s, and d^s are the payoffs of group A^s with different strategies; and e^s, f^s, g^s, and h^s are the payoffs of group B^s with different strategies.

TABLE AI
2×2 EVOLUTIONARY GAME BENEFIT MATRIX

Strategy	Element of matrix	
	Strategy $B_2^s(1-x^s)$ (group B^s)	Strategy $B_1^s(x^s)$ (group B^s)
Strategy $A_1^s(y^s)$ (group A^s)	a^s, e^s	b^s, f^s
Strategy $A_2^s(1-y^s)$ (group A^s)	c^s, g^s	d^s, h^s

If the pure strategy of group A^s is A_1^s, the payoff expectation of the group is:

$$E\left(A_1^s\right)=a^s\left(1-x^s\right)+b^s x^s \tag{A1}$$

If the pure strategy of group A^s is A_2^s, the payoff expectation of the group is:

$$E\left(A_2^s\right)=c^s\left(1-x^s\right)+d^s x^s \tag{A2}$$

Therefore, when the mixed strategy in which the proportion of selecting strategy A_1^s is y^s and proportion of selecting strategy A_2^s is $1-y^s$, the payoff expectation of group A^s is:

$$E\left(A^s\right)=y^s E\left(A_1^s\right)+\left(1-y^s\right)E\left(A_2^s\right)= y^s\left[a^s(1-x^s)+b^s x^s\right]+\left(1-y^s\right)\left[c^s\left(1-x^s\right)+d^s x^s\right] \tag{A3}$$

Similarly, the payoff expectations of group B^s with pure strategies of B_1^s and B_2^s can be represented as:

$$E\left(B_1^s\right)=e^s\left(1-y^s\right)+g^s y^s \tag{A4}$$

$$E\left(B_2^s\right)=f^s\left(1-y^s\right)+h^s x^s \tag{A5}$$

$$E\left(B^s\right)=\left(1-x^s\right)E\left(B_1^s\right)+x^s E\left(B_2^s\right)= \left(1-x^s\right)\left[e^s y^s+g^s\left(1-y^s\right)\right]+x^s\left[f^s y^s+h^s\left(1-y^s\right)\right] \tag{A6}$$

The growth rate of proportion sharing strategy A_1^s in group A^s can be regarded as the difference between the current payoff expectation of the strategy and the payoff expectation of the overall mixed strategy, which yields the corresponding dynamics:

$$\dot{y}^s=\left(E\left(A_1^s\right)-E\left(A^s\right)\right)y^s \tag{A7}$$

Similarly, the evolutionary dynamics of proportion sharing strategy B_2^{s1} in group B^s can be represented as:

$$\dot{x}^s=\left(E\left(B_2^s\right)-E\left(B^s\right)\right)x^s \tag{A8}$$

Substituting (A1), (A3), (A5), and (A6) into (A7) and (A8), the dynamic equations of the 2×2 evolutionary game are:

$$\dot{x}^s=x^s\left(1-x^s\right)\left[\left(f^s-e^s+g^s-h^s\right)y^s-\left(g^s-h^s\right)\right] \tag{A9}$$

$$\dot{y}^s=y^s\left(1-y^s\right)\left[\left(a^s-c^s\right)-\left(a^s-c^s+d^s-b^s\right)x^s\right] \tag{A10}$$

The solution curves of above equations represent the dynamic evolution process of the game. And stable solutions of the dynamic system (A9) and (A10) are the evolutionary stable strategies of this 2×2 evolutionary game. When an equilibrium point of the dynamic system (A9) and (A10) satisfies the criterion of evolutionary stable equilibrium proposed in theorem 1, it is an evolutionary stable equilibrium point corresponding to an evolutionary stable strategy which can resist the aggression of small mutations.

All equilibrium points of the system (A9) and (A10) can be solved as $E_1^s(0,0)$, $E_2^s(1,0)$, $E_3^s(0,1)$, $E_4^s(1,1)$, and when $0<(a^s-c^s)/(a^s-c^s+d^s-b^s)$, $(g^s-h^s)/(f^s-e^s+g^s-h^s)<1$, $E_5^s((a^s-c^s)/(a^s-c^s+d^s-b^s), (g^s-h^s)/(f^s-e^s+g^s-h^s))$ is also an equilibrium point. All the equilibrium points correspond to one evolutionary game equilibrium situation, respectively, but some of them are not stable. To determine whether the equilibrium point is stable or not, one can recall the local stability criterion of Lyapunov stability theory. That is the Jacobian matrix $\boldsymbol{J}$ is negative definiteness, i.e., det($\boldsymbol{J}$) has negative real parts. Based on the fact that the sum of eigenvalues equals to the trace of square matrix and the product of eigenvalues equals to the determination of square matrix. Therefore, the conditions of det($\boldsymbol{J}$)>0 and tr($\boldsymbol{J}$)< 0 guarantee negative definiteness of 2×2 Jacobian matrix of the game. This finishes the proof.

Jacobian matrix corresponding to the replicator dynamics equations (A9) and (A10) is:

$$\boldsymbol{J}=\begin{bmatrix}\left(1-2x^s\right)\left[\left(f^s-e^s+g^s-h^s\right)y^s-\left(g^s-h^s\right)\right] & x^s\left(1-x^s\right)\left(f^s-e^s+g^s-h^s\right)\\ y^s\left(y^s-1\right)\left(a^s-c^s+d^s-b^s\right) & \left(1-2y^s\right)\left[\left(a^s-c^s\right)-\left(a^s-c^s+d^s-b^s\right)x^s\right]\end{bmatrix} \tag{A11}$$

The stability analysis of five equilibrium points according to theorem 1 is shown in Table AII.

TABLE AII
STABILITY ANALYSIS OF EQUILIBRIUM POINTS

Equilibrium point	det($\boldsymbol{J}$)	tr($\boldsymbol{J}$)
E_1^s	$(a^s-c^s)(h^s-g^s)$	$(a^s+h^s)-(c^s+g^s)$
E_2^s	$(d^s-b^s)(h^s-g^s)$	$(b^s+g^s)-(d^s+h^s)$
E_3^s	$-(a^s-c^s)(f^s-e^s)$	$(c^s+f^s)-(a^s+e^s)$
E_4^s	$-(d^s-b^s)(f^s-e^s)$	$(d^s+e^s)-(b^s+f^s)$
E_5^s	$\dfrac{(a^s-c^s)(d^s-b^s)(f^s-e^s)(g^s-h^s)}{(a^s-c^s+d^s-b^s)(f^s-e^s+g^s-h^s)}$	0

In this 2×2 evolutionary game, all asymptotically stable points are located at the vertexes of value intervals of x^s and y^s, and have no connection with the initial values of x^s and y^s. It can be seen that there is no stable equilibrium point between $(0,1)$. The stability of $E_1^s(0,0)$, $E_2^s(1,0)$, $E_3^s(0,1)$, $E_4^s(1,1)$ depends on the payoff parameters. For example, if $a^s<c^s$ and $h^s<g^s$, $E_1^s(0,0)$ is an evolutionary stable equilibrium point; if $b^s<d^s$ and $e^s>f^s$, $E_2^s(1,0)$ is an evolutionary stable equilibrium point; if $a^s>c^s$ and $e^s>f^s$, $E_3^s(0,1)$ is an evolutionary stable equilibrium point; if $b^s>d^s$ and $e^s<f^s$, $E_4^s(1,1)$ is an evolutionary stable equilibrium point. $E_5^s((a^s-c^s)/(a^s-c^s+d^s-b^s), (g^s-h^s)/(f^s-e^s+g^s-h^s))$ is an equilibrium point but is not evolutionarily stable.

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