Research on Cooperative Strategy of Clean Energy Grid-connected Subjects based on Evolutionary Game Model

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Abstract. Evolutionary game theory, based on the assumption of bounded rationality of individuals and taking group behavior as the research object, is the result of integrating evolutionary biology theory into classical game theory. Based on the complex braking dynamic equation between clean energy power generation enterprises and power grid enterprises, the coordinates of unstable equilibrium points and saddle points in the evolutionary system are calculated, and the dynamic evolutionary phase diagram of the game system is formed. According to the variation of system evolutionary behavior parameters, the model further differentiates into five evolutionary results in the strategy set (cooperation, non-cooperation) of two players. The results show that the long-term evolutionary equilibrium results of the two sides are completely cooperative or completely non-cooperative, depending on the relation of inequality of the area above and below the critical line of the dynamic evolutionary phase diagram.

Keywords: Evolutionary game theory, evolutionary biology theory, clean energy power generation enterprises, complex braking dynamic equation, dynamic evolutionary phase diagram.

1. Introduction

Entering the 21st century, energy security and environmental protection have become a problem of globalization. The Chinese government regards the development of clean energy as an important part of China's basic energy strategy, and has formulated a series of incentive policies to guide and encourage the development of clean energy. However, with the continuous expansion of the scale, the bottleneck problem faced by China's clean energy development has become increasingly prominent. Under the current situation that the proportion of clean energy generation in total electricity is only about 2%, the key problem to restrict the grid-connected clean energy generation is the distribution and coordination of benefits [1,2].

This paper uses evolutionary game theory to analyse the relationship between clean energy power generation enterprises and power grid enterprises, and regards the interest balance between them as a "learning" evolutionary system [3].

Evolutionary game theory is a theoretical analysis method based on Darwin's biological evolution theory, which combines game theory analysis with dynamic evolutionary process analysis, starting from the assumption of limited rationality of individuals and taking group behaviour as the research object. The key concepts in evolutionary game theory are Evolutionary Stable Strategy (ESS) [4].

2. Evolutionary Game Model of Clean Energy Interest Coordination in Grid Connection

2.1 Establishment of Payment Matrix for Game Parties

To mobilize the initiative of grid enterprises to respond to the grid-connected demand of clean energy generation, it is necessary to respect the reasonable interests of grid enterprises so as to enable them to serve the process of clean energy generation enterprises and realize their service value. Power grid enterprises and clean energy power generation enterprises should share the excess profits generated by the cooperation between the two sides. Both sides should maximize their own interests and play a strategic game with each other. The set of strategies is (cooperation, non-cooperation). It is formed spontaneously by the principle of "natural selection of things, survival of the fittest" [5]. According to the strategy choices of other stakeholders, each stakeholder considers the relative adaptability in his own group, and then chooses and adjusts his own strategy.

Suppose that R_1 and R_2 represent the normal benefits of non-cooperative strategies adopted by clean energy power generation enterprises and power grid enterprises, respectively. $Ri=W_i \Delta S_i$, W_i denotes the discount factor of the player *i* and has $0 \leq W_i < 1$; ΔS represents the total excess profits of the two players when they adopt cooperative strategies respectively. λ is the distribution coefficient of total excess profit ΔS for power grid enterprises. Then the payment matrix of both sides of the game can be obtained as Tab.1.

Tab.1 Payment Matrix of Power Grid Enterprises and Clean Energy Power Generation Enterprise

		Power Grid Enterprises	
		cooperation	Non-cooperation
Clean Energy Power Generation Enterprise	cooperation	$R_1+(1-\lambda)\Delta S-l_1\Delta Q$, $R_2+\lambda\Delta S-l_2\Delta Q$	$R_1+V_1\Delta Q-l_1\Delta Q, R_2$
	Non-cooperation	$R_1, R_2+V_2\Delta Q-l_2\Delta Q$	R_1, R_2

In the payment matrix, Q and ΔQ represent the output increment of clean energy power generation enterprises when choosing non-cooperative strategy and when choosing cooperative strategy respectively. It is assumed that the power generation enterprises need to fix production. $l_i\Delta Q$ is the initial cost incurred by the player i when he adopts the cooperative strategy; l_i is the incremental cost of increasing the supply (or service) of a unit of clean energy. It is assumed that when both sides adopt cooperative strategies, their excess profits are greater than their initial costs.

According to the hypothesis, it can be concluded that:

$$R_1=(p+V_1)Q \tag{1}$$

$$R_2=pQ \tag{2}$$

$$\Delta S=(2p+V_1+V_2-l_1-l_2)\Delta Q \tag{3}$$

In the formula, *p* represents the selling price of conventional energy power for power grid enterprises, and V_i is the subsidy for the supply (or service) of clean energy power per unit.

2.2 Establishment of Evolutionary Process for Game Parties

Assuming that the proportion of clean energy power generation enterprises choosing cooperative strategy is *x*, the proportion of non-cooperative strategy is 1-*x*; the proportion of grid enterprises choosing cooperative strategy is *y*, and the proportion of non-cooperative strategy is 1-*y*.

The expected benefit of clean energy power generation enterprises when choosing cooperation strategy is as follows:

$$u_1^s=y[R_1+(1-\lambda)\Delta S-l_1\Delta Q]+(1-y)(R_1+V_1\Delta Q-l_1\Delta Q) \tag{4}$$

When clean energy power generation enterprises choose non-cooperative strategies, the expected benefit is as follows:

$$u_1^n=yR_1+(1-y)R_1 \tag{5}$$

The average expected benefit is:

$$\overline{u}_1 = xu_1^s + (1-x)u_1^n \tag{6}$$

Similarly, the average expected benefit of power grid enterprises is as follows:

$$\overline{u}_2 = yu_2^s + (1-y)u_2^n \tag{7}$$

The complex braking dynamic equation of the two players is constructed as follows:

$$\frac{dx}{dt} = x(u_1^s - \overline{u}_1) = x(1-x)\{[(1-\lambda)\Delta S - V_1\Delta Q]y + (V_1 - l_1)\Delta Q\} \tag{8}$$

$$\frac{dy}{dt} = y(u_2^s - \overline{u}_2) = y(1-y)[(\lambda\Delta S - V_2\Delta Q)x + (V_2 - l_2)\Delta Q] \tag{9}$$

Dynamic equations (8) and (9) describe the population dynamics of the evolution of the system. From the above analysis of the stability of the system, it can be seen that there are five local equilibrium points in the region $s = \{(x, y); 0 \le x, y \le 1\}$, namely O (0,0), A (1,0), B (0,1), C (1,1) and D (x_D, y_D).Among them, $x_D = \frac{(l_1 - V_1)\Delta Q}{(1-\lambda)\Delta S - V_1\Delta Q}$, $y_D = \frac{(l_2 - V_2)\Delta Q}{\lambda\Delta S - V_2\Delta Q}$.

Fig. 1 depicts the evolution of the game between clean energy power generation enterprises and power grid enterprises. The broken line ADB is a critical line, which is composed of two unstable equilibrium points (point A and point B) and saddle point (point D) in the evolutionary system. If the initial game is in the upper right of the broken line ADB (ADBC part), the evolutionary system will converge to point C, that is, all stakeholders choose cooperative strategies; if the initial game is in the lower left side of the broken line ADB (ADBO part), the evolutionary system will converge to O point, that is, all stakeholders choose non-cooperative strategy. The arrow in the figure shows the dynamic evolution direction of the game between the two sides in the region. Because the evolution of the system is a dynamic process, the system may be in a state of coexistence of cooperation and non-cooperation among stakeholders in a certain period of time.

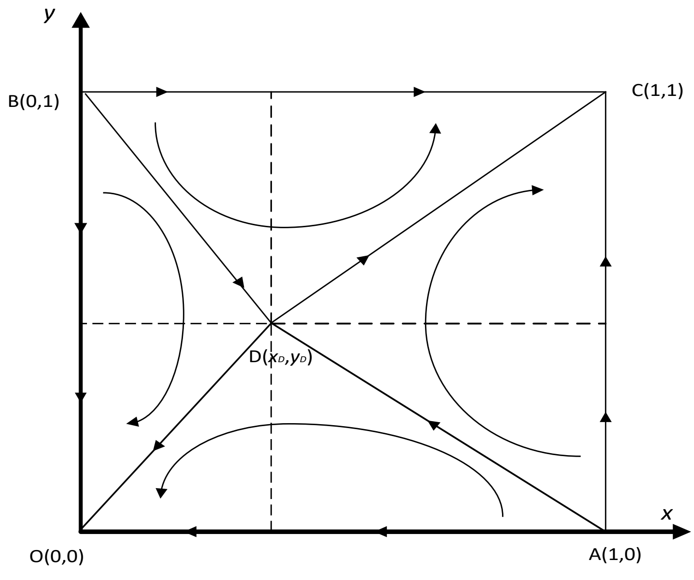

Fig.1 Dynamic Evolution Phase Diagram of Systems

3. Model Analysis

According to the different parameters affecting the evolution behavior of the system, the evolution results and control methods are discussed as follows:

Situation 1:

When $\begin{cases} R_1+(1-\lambda)\Delta S-l_1\Delta Q>R_1 \\ R_1+V_1\Delta Q-l_1\Delta Q>R_1 \\ R_2+\lambda\Delta S-l_2\Delta Q>R_2 \\ R_2+V_2\Delta Q-l_2\Delta Q>R_2 \end{cases}$, $\begin{cases} \dfrac{l_2}{2p+V_1+V_2-l_1-l_2}<\lambda<\dfrac{2p+V_1+V_2-2l_1-l_2}{2p+V_1+V_2-l_1-l_2} \\ V_1>l_1 \\ V_2>l_2 \end{cases}$ is obtained.

In this case, it means that the initial investment cost is small, the benefits are considerable, and both sides can accept the excess income distribution scheme generated by cooperation. Other clean energy power generation enterprises and power grid enterprises will compete to follow suit and eventually evolve into a stable state in which all organizations adopt cooperative strategies.

Situation 2:

When $\begin{cases} R_1+(1-\lambda)\Delta S-l_1\Delta Q>R_1 \\ R_1+V_1\Delta Q-l_1\Delta Q<R_1 \\ R_2+\lambda\Delta S-l_2\Delta Q>R_2 \\ R_2+V_2\Delta Q-l_2\Delta Q<R_2 \end{cases}$, $\begin{cases} \dfrac{l_2}{2p+V_1+V_2-l_1-l_2}<\lambda<\dfrac{2p+V_1+V_2-2l_1-l_2}{2p+V_1+V_2-l_1-l_2} \\ V_1<l_1 \\ V_2<l_2 \end{cases}$ is obtained.

Because of the large initial investment (or less subsidies), both sides may choose cooperation strategy or non-cooperation strategy at the same time. If the excess profit *ΔS* produced by cooperation is relatively large, the area of ADBC above the break line in Fig. 1 is also large. Then, the probability that the system converges to equilibrium point C will increase, that is, both sides prefer to choose cooperative strategy at the same time.

Situation 3:

When $\begin{cases} R_1+(1-\lambda)\Delta S-l_1\Delta Q<R_1 \\ R_1+V_1\Delta Q-l_1\Delta Q<R_1 \\ R_2+\lambda\Delta S-l_2\Delta Q<R_2 \\ R_2+V_2\Delta Q-l_2\Delta Q<R_2 \end{cases}$, $\begin{cases} \dfrac{2p+V_1+V_2-2l_1-l_2}{2p+V_1+V_2-l_1-l_2}<\lambda<\dfrac{l_2}{2p+V_1+V_2-l_1-l_2} \\ V_1<l_1 \\ V_2<l_2 \end{cases}$ is obtained.

Further, $\begin{cases} 2p+V_1+V_2<2(l_1+l_2) \\ V_1<l_1 \\ V_2<l_2 \end{cases}$, that is, $p<\dfrac{l_1+l_2}{2}$.

At this time, compared with the initial cost, the price of conventional energy power generation is lower, and clean energy power is far from competitive. No matter how the benefits are distributed, neither side is willing to cooperate.

Situation 4:

When $\begin{cases} R_1+(1-\lambda)\Delta S-l_1\Delta Q>R_1 \\ R_1+V_1\Delta Q-l_1\Delta Q>R_1 \\ R_2+\lambda\Delta S-l_2\Delta Q>R_2 \\ R_2+V_2\Delta Q-l_2\Delta Q<R_2 \end{cases}$, $\begin{cases} \dfrac{l_2}{2p+V_1+V_2-l_1-l_2}<\lambda<\dfrac{2p+V_1+V_2-2l_1-l_2}{2p+V_1+V_2-l_1-l_2} \\ V_1>l_1 \\ V_2<l_2 \end{cases}$ is obtained.

For clean energy power generation enterprises, the subsidy rate is greater than the marginal cost of initial investment, that is, it is profitable to choose cooperation strategy, which makes most clean energy power generation enterprises willing to invest, and also willing to give the excess profits generated by cooperation to grid enterprises in a certain proportion. Although the subsidy rate for power grid enterprises is relatively low, as long as the distribution of benefits is reasonable, power grid enterprises can cooperate with them.

Situation 5:

When $\begin{cases} R_1+(1-\lambda)\Delta S-l_1\Delta Q>R_1 \\ R_1+V_1\Delta Q-l_1\Delta Q<R_1 \\ R_2+\lambda\Delta S-l_2\Delta Q<R_2 \\ R_2+V_2\Delta Q-l_2\Delta Q<R_2 \end{cases}$, $\begin{cases} \lambda<\dfrac{2p+V_1+V_2-2l_1-l_2}{2p+V_1+V_2-l_1-l_2} \\ \lambda<\dfrac{l_2}{2p+V_1+V_2-l_1-l_2} \\ V_1<l_1 \\ V_2<l_2 \end{cases}$ is obtained.

Referring to situation 3, if $p<\frac{l_1+l_2}{2}$, both sides are unwilling to cooperate, because the price of clean energy power is far from competing with conventional energy power and subsidies cannot meet the initial input needs of both sides. If $p>\frac{l_1+l_2}{2}$, clean energy power, despite the possibility of competing with conventional energy power in terms of price, is unacceptable to both sides for the benefit allocation scheme. As a result, both sides tend to choose non-cooperative strategies, and the results are the same as those in situation 3.

4. Conclusion

In this paper, evolutionary game theory is applied to the study of interest coordination mechanism between clean energy power generation enterprises and power grid enterprises. The formation of interest balance between clean energy power generation enterprises and grid enterprises is a dynamic and gradual evolution process. The evolution direction of the strategies of both sides of the game is related to their payment matrix and is affected by the initial parameters of the system. Among them, excess profit ΔS, conventional energy price p, subsidy rate V, marginal cost of initial input l and distribution coefficient λ are important factors in the evolution of bilateral cooperation relationship.

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