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The Analysis with Game Theory Model on Quantity of Electricity Produced by the Two-Oligopoly Generation Companies

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Abstract: Considering that the generation companies are finitely rational individuals, this study analyzes the Game Theory Model on quantity of electricity produced by the two-oligopoly generation companies. The Nash-Cournot equilibrium point is obtained by using the game theory and stability theory. The excessive competition of electricity markets usually results in some disorderly market actions, which will destroys the structure and operation in markets. We distinguish the chaos actions of the game system with the electric generation based on the numerical method. The approach to control the chaos actions in electricity markets is studied and the result shows that reducing the speed of adjusting the quantity of electricity of the generation companies and the highest electricity price that the governments allow can restrain the appearance of the chaos electricity markets effectively.

Keywords: generation companies; game theory; Nash equilibrium; chaos.

1 Introduction

Electricity industry is the basic industry of a country. However, the electricity markets are not generally free competition markets and they are oligopoly markets. With the development of the reformation in electricity markets, many researchers at home and abroad have investigated the oligopoly electricity markets. Building the simulation systems in electricity markets or starting the simulation study in electricity markets has become a common understanding among the researchers [1,2].

The problem that how to choose the optimal strategy when many decision subjects of the markets stand in the limited-condition markets competition can been solved by the game theory [3-5]. The quantity of electricity produced by generation companies is the private information in the current electricity markets. Hence, electricity markets are similar to a incomplete-information game problem. The researchers have made many investigations of the electricity markets by the game theory method [6-8]. Yang has discussed the Complex dynamics analysis for Cournot Game with bounded rationality in electricity markets [9]. Ladjici has studied the game actions between the the generation subjects in deregulated electricity markets and investigated the centralized or bilateral structure to find the Nash equilibrium point in oligopoly markets [10]. Ma has researched the repeated game model in electric power triopoly based on analyzing the effects that wheeling cost rate has on the output and profit in generation companies. This result shows that it will increase the production cost in generation companies if the wheeling cost rate is relatively large. Hence, it is very possible to raise the electricity price to transfer the production cost for the generation companies and it will hurt customers interests [11].

The competition has been introduced into the generation area by the electricity industries in our country and the process of the power generation and power transmission has been changed from integrated dispatch to business-form trading exchange now. It is certain to hope to maximize its interests under the current market clearing price for the generation companies as rational economic man. However, it will cause a series of disorderly actions when the markets compete excessively. Aside from the game processes between the generation companies, the instability and complexity of the competitive results will keep the electricity markets in chaos easily. The power network is required to must plan to

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make the system keep working in advance by these characteristic in electricity system because in addition to the power that can not be kept in mass storage economically, the suppliers and buyers need to guarantee the spot balance. But the power that the generation companies expect to generate fluctuates greatly in chaos electricity markets and this situation will destroy the structure and operation in markets seriously. Many researchers have made many investigations of the chaos models at present [12-14]. Mohandas [15] introduces a Distributed Generation (DG) unit in the distribution system to improves the voltage profile and reduces the system losses [16]. Zhang has analyzed chaos control of dynamic bidding systems and obtained that Nash equilibrium of oligopoly bidding dynamics is maintainable if suitable control variables and parameters are chosen by state delayed feedback control method and numerical simulations.

This paper obtains the Nash-Cournot equilibrium point in the game model of power generation based on the Cournot game model of the quantity of electricity produced by the generation companies and the stability theory. The chaos actions can be recognized by the numerical simulation method in the game system of power generation. We studied how to control the chaos actions in electricity markets effectively according to the actual controlling method in electricity markets. The final result shows that the chaos electricity markets can be restrained through changing the speed of adjusting the quantity of electricity of the generation companies or reducing the highest electricity price that the governments allow.

2 The game model of the power generation

This model assumes that there are only two generation companies and they adopt their own production strategy respectively to maximize their interests. The generation companies are independently economic subjects and possess of the ability to make decisions independently and adapt themselves. They should adjust the current quantity of power generation according to the previous benefit.

Make sure the clearing price in electricity markets firstly. If $q_1(t)$ and $q_2(t)$ represent the quantity of power generation of generation companies 1 and 2 at time t respectively, then the clearing price in electricity markets at time t can be in forms of:

$$p(t) = A - B(q_1(t) + q_2(t)), \tag{1}$$

where $A > 0$ represents the highest electricity price that the governments allow, $B > 0$ represents the coefficient of markets and total quantity of power generation. The electricity price will decrease with the increasing of the quantity of power generation in markets according to equation (1). The generation cost is related to its quantity of power generation for the generation companies and generally increases with the increasing of the quantity of power generation. The generation cost of $i(i = 1, 2)$ generation company can be calculated

$$F_i(t) = a_i + b_i q_i(t) + C_i(q_i(t))^2, \qquad (i = 1, 2), \tag{2}$$

where a_i is the intercept of the generation cost curve in generation company i, which represents the fixed cost of power station and b_i, c_i are non-negative coefficients. Each generation company decides the quantity of power generation according to maximizing their own interest rate in the choice to generation strategy in generation companies. The benefit of generation company $i(i = 1, 2)$ at time t can be calculated

$$\pi_i(t) = q_i(t)p(t) - F_i(t) = q_i(t)(A - B(q_1(t) + q_2(t))) - (a_i + b_i q_i(t) + C_i(q_i(t))^2), \tag{3}$$

The marginal income at time t in generation companies can be calculated

$$\begin{cases} \frac{\partial \pi_1(t)}{\partial q_1(t)} = A - b_1 - 2(B + C_1)q_1(t) - Bq_2(t), \\ \frac{\partial \pi_2(t)}{\partial q_2(t)} = A - b_2 - 2(B + C_2)q_2(t) - Bq_1(t). \end{cases} \tag{4}$$

The game between generation companies appears in the actual electricity markets all the time and the decision to companies is a repeated dynamic process at the long term. The generation companies will adjust the current quantity of power generation according to the early yield and marginal income. The reaction function that producers have on competitors can be calculated at sometime in markets by the equation. It is also called the optimal yield that producers have on the opponent yield at a fixed period in all possibly putative situations, which is named as the Nash-Cournot equilibrium. However, the game between production enterprises is always going on in actual markets. So the choice to enterprises is a repeated dynamic process whose actions possess of the adaption and long-term memory at the long term and it follows the adjusting process based on the early marginal income ratio. The repeated Cournot game model of the dynamic adjustment is the dynamic adjustment of the quantity of electricity produced by generation companies and it can be in forms of

$$\begin{cases} q_1(t+1) = q_1(t) + \lambda_1 q_1(t)\frac{\partial \pi_1(t)}{\partial q_1(t)} = (1+\lambda_1 A - \lambda_1 b_1)q_1(t) - 2(B+C_1)\lambda_1 q_1^2(t) - \lambda_1 B q_1(t)q_2(t), \\ q_2(t+1) = q_2(t) + \lambda_2 q_2(t)\frac{\partial \pi_2(t)}{\partial q_2(t)} = (1+\lambda_2 A - \lambda_2 b_2)q_2(t) - 2(B+C_1)\lambda_2 q_2^2(t) - \lambda_2 B q_1(t)q_2(t), \end{cases} \tag{5}$$

where $\lambda_i \geq 0$ represents the adjusting speed of power generation of generation company $i(i = 1, 2)$. Especially, $\lambda_i = 0$ $(i = 1, 2)$, this indicates that generation companies are not sensitive to electricity demand in markets and their own benefit. Besides, the power generation will stay in an unchanged situation all the time.

3 The analysis of the equilibrium points

Each generation company chooses the quantity of power generation according to maximizing their benefit in the game of electricity yield of generation companies. Four equilibrium points can be obtained by the equation and they are

$$E_1 = (0,0), \quad E_2 = \left(\frac{A-b_1}{2(B+c_1)}, 0\right), \quad E_3 = \left(0, \frac{A-b_2}{2(B+c_2)}\right),$$

$$E_4 = \left(\frac{2(A-b_1)(B+c_2)-(A-b_2)B}{4(B+c_1)(B+c_2)-B^2}, \frac{2(A-b_2)(B+c_1)-(A-b_1)B}{4(B+c_1)(B+c_2)-B^2}\right)$$

We can know that equilibrium points E_1, E_2 and E_3 are three boundary equilibrium points at the margin of the strategy space set $S = \{(q_1, q_2)|q_1 \geq 0, q_2 \geq 0\}$ and E_4 is the only Nash-Cournot equilibrium point. The stability of each equilibrium point will be analyzed next. Then we will analyze the dynamics of the game model in power generation. The Jacobian matrix can be calculated:

$$J = \begin{pmatrix} \lambda_1 A - \lambda_1 b_1 - 4(B+c_1)\lambda_1 q_1^* - \lambda_1 B q_2^* & -\lambda_1 B q_1^* \\ -\lambda_2 B q_2^* & \lambda_2 A - \lambda_2 b_2 - \lambda_2 B q_1^* - 4\lambda_2(B+c_2)q_2^* \end{pmatrix} \tag{6}$$

where q_1^* and q_2^* represent the equilibrium points of the equation.

Lemma 1 *This is the n dimensional discrete dynamical system and all the eigenvalues of Jacobian matrix $J(x^*)$ of the right function in this system must satisfy the condition that $|\lambda| < 1$ in order to stabilize the equilibrium point x^*.*

$$\begin{cases} x_1(t+1) = f_1(x_1(t), x_2(t), \cdots, x_n(t)), \\ x_2(t+1) = f_2(x_1(t), x_2(t), \cdots, x_n(t)), \\ \cdots \\ x_n(t+1) = f_n(x_1(t), x_2(t), \cdots, x_n(t)). \end{cases} \tag{7}$$

We will analyze the stability of each equilibrium point based on the lemma 3.1 next.

(1). $J_1 = \begin{pmatrix} \lambda_1 A - \lambda_1 b_1 & 0 \\ 0 & \lambda_2 A - \lambda_2 b_2 \end{pmatrix}$ can be calculated at equilibrium point $E_1 = (0, 0)$. Then we can calculate two eigenvalues of Jacobian matrix and they are $\bar{\lambda}_1 = \lambda_1 A - \lambda_1 b_1$, $\bar{\lambda}_2 = \lambda_2 A - \lambda_2 b_2$. According to the lemma 3.1, if $\bar{\lambda}_1 \leq 1$ and $\bar{\lambda}_2 \leq 1$, that is $A \leq \min\{b_1, b_2\}$, then equilibrium point E_1 is the stable, otherwise, equilibrium point E_1 is unstable if $A > \min\{b_1, b_2\}$.

(2). $J_2 = \begin{pmatrix} \lambda_1(b_1 - A) & -\frac{\lambda_1 B(A-b_1)}{2(B+c_1)} \\ 0 & \lambda_2(A-b_2) - \frac{\lambda_2 B(A-b_1)}{2(B+c_1)} \end{pmatrix}$ can be calculated at equilibrium point $E_2 = \left(\frac{A-b_1}{2(B+c_1)}, 0\right)$. We can obtain two eigenvalues of Jacobian matrix: $\bar{\lambda}_1 = \lambda_1(b_1 - A)$, $\bar{\lambda}_2 = \lambda_2(A - b_2) - \frac{\lambda_2 B(A-b_1)}{2(B+c_1)}$. According to the lemma 3.1, if $\bar{\lambda}_1 \leq 1$ and $\bar{\lambda}_2 \leq 1$, that is $A \in \left[b_1, b_2 + \frac{B(A-b_1)}{2(B+c_1)}\right]$, then equilibrium point E_2 is stable, otherwise, if $A \notin \left[b_1, b_2 + \frac{B(A-b_1)}{2(B+c_1)}\right]$, equilibrium point E_2 is unstable.

(3). $J_3 = \begin{pmatrix} \lambda_1(A-b_1) - \frac{\lambda_1 B(A-b_2)}{2(B+c_2)} & 0 \\ -\frac{\lambda_2 B(A-b_2)}{2(B+c_2)} & \lambda_2(b_2 - A) \end{pmatrix}$ can be calculated at equilibrium point $E_3 = \left(0, \frac{A-b_2}{2(B+c_2)}\right)$. Two eigenvalues of Jacobian matrix are $\bar{\lambda}_1 = \lambda_1(A - b_1) - \frac{\lambda_1 B(A-b_2)}{2(B+c_2)}$ and $\bar{\lambda}_2 = \lambda_2(b_2 - A)$. According to the lemma 3.1, if $\bar{\lambda}_1 \le 1$ and $\bar{\lambda}_2 \le 1$, that is $A \in \left[b_2, b_1 + \frac{B(A-b_2)}{2(B+c_2)}\right]$, then equilibrium point E_3 is stable, otherwise, if $A \notin \left[b_2, b_1 + \frac{B(A-b_2)}{2(B+c_2)}\right]$, equilibrium point E_3 is unstable.

(4). $J_4 = \begin{pmatrix} \lambda_1(A-b_1) - 4(B+c_1)\lambda_1 q_1^* - \lambda_1 B q_2^* & -\lambda_1 B q_1^* \\ -\lambda_2 B q_2^* & \lambda_2(A-b_2) - \lambda_2 B q_1^* - 4\lambda_2(B+c_2)q_2^* \end{pmatrix}$ can be calculated at equilibrium point $E_4 = \left(\frac{2(A-b_1)(B+c_2)-(A-b_2)B}{4(B+c_1)(B+c_2)-B^2}, \frac{2(A-b_2)(B+c_1)-(A-b_1)B}{4(B+c_1)(B+c_2)-B^2}\right)$, where $q_1^* = \frac{2(A-b_1)(B+c_2)-(A-b_2)B}{4(B+c_1)(B+c_2)-B^2}$, $q_2^* = \frac{2(A-b_2)(B+c_1)-(A-b_1)B}{4(B+c_1)(B+c_2)-B^2}$. The characteristic equation of Jacobian matrix J_4 is $\lambda^2 - tr(J_4)\lambda + \det(J_4) = 0$, where $tr(J_4)$ represents the trace of Jacobian matrix J_4 and $\det(J_4)$ represents the determinant of Jacobian matrix J_4. According to Schur-Cohn criterion, equilibrium point E_4 is stable if (i). $1 - tr(J_4 + \det(J_4)) > 0$, (ii) $1 + tr(J_4 + \det(J_4)) > 0$ and (iii) $|1 \pm \det(J_4)| > 0$.

The generation companies will reach the Nash equilibrium point after experiencing finitely repeated games. Therefore, all the generation companies do not improve their yield and do not lower their yield too. Then the electricity markets will stay in stable situation temporarily. The stable Nash-Cournot equilibrium point shows that the quantity of power generation in generation companies will tend to be stable at the equilibrium point in finite games after the generation companies adjust their quantity of power generation constantly even if the initial quantity of power generation in generation companies is different. However, the unstable equilibrium point shows that the stability of equilibrium point will be destroyed. Then the system will appear the bifurcation phenomenon possibly, even evolve into chaos state and the markets will compete disorderly.

4 The numerical analysis of dynamic characteristic in model

The competition has been introduced into the generation area by the electricity industries in our country and the process of the power generation and power transmission has been changed from integrated dispatch to business-form trading exchange now. It is certain to hope to maximize its interests under the current market clearing price for the generation companies as rational economic man. However, it will cause a series of disorderly market actions (Eg. chaos) when the markets compete excessively and this situation will destroy the structure and operation in markets seriously. Therefore, it is very meaningful for the survival and development of the generation companies if they can use the information they have owned according to the electricity consumption situation in actual areas and use contemporary and economic analysis tools to make reasonable choice.

The generation companies will make an expectation on the next electricity demand according to the information they have owned. The speed of adjusting the quantity of electricity of the generation companies has a big impact on the stability of markets.The regulation that governments have on the market price also has a great influence on the stability of markets at the same time. The figure 1 shows the change maps with the speed of adjusting the quantity of power generation λ_1, λ_2 between the quantity of power generation and the largest Lyapunov exponent in generation companies in order to recognize the chaos actions of the game system of power generation. Then the figure 2 shows the change maps with the highest electricity price that the governments allow A between the quantity of power generation and the largest Lyapunov exponent in generation companies. Figure 1 shows the bifurcation diagrams and the largest Lyapunov exponent diagrams. Figure 1 (a) shows the change trend of the quantity of power generation in generation company 1 with the speed of adjusting the quantity of power generation λ. Figure 1 (b) shows the change trend of the quantity of power generation in generation company 2 with the speed of adjusting the quantity of power generation λ.

We denote $A = 3, B = 0.005, b_1 = 0.46, b_2 = 0.51, c_1 = 1.15, c_2 = 0.98, \lambda_1 = \lambda_2 = \lambda$, and denote $q_1(0) = 0.26, q_2(0) = 0.33$, the initial quantity of two generation companies. Figure 1 shows the bifurcation diagram of the system with the change of λ and the largest Lyapunov exponent.

We can find that q_1 and q_2 converge to the equilibrium points if $\lambda < 0.77$ from Figure 1. This illustrates that it will benefit the power generation in markets and keep the demand stable at the Nash equilibrium point when the speed of adjusting the quantity of power generation in generation companies is at a smaller range. The system will stay at the period-doubling bifurcation situation and become unstable if $0.77 < \lambda < 0.95$. The equilibrium point will become more unstable with the increasing of λ and the system will be in chaos when the Lyapunov exponent is bigger than 0. The markets will become unusually unstable when the finitely rational generation companies adjust the speed of power generation too quickly and the markets will compete disorderly.

We denote $B = 0.005, b_1 = 0.46, b_2 = 0.51, c_1 = 1.15, c_2 = 0.98, \lambda_1 = \lambda_2 = \lambda$, and denote $q_1(0) = 0.26, q_2(0) = 0.33$ the initial quantity of two generation companies. Figure 2 shows the bifurcation diagram of the system with the

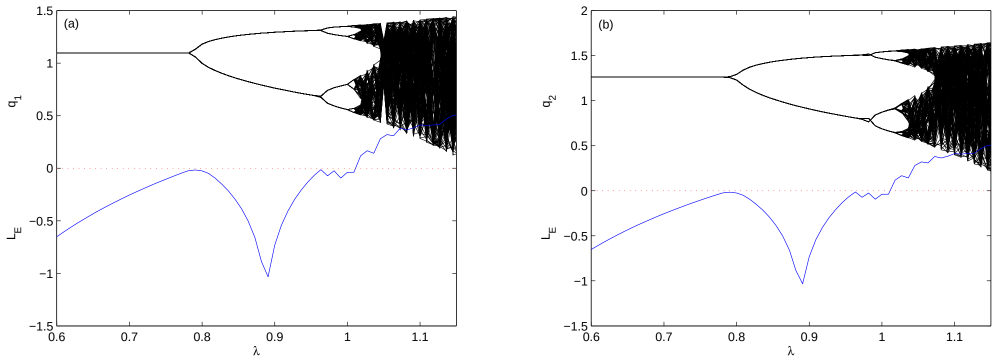


Figure 1: The bifurcation diagrams and the largest Lyapunov exponent diagrams. (a). The company 1; (b). The company 2.

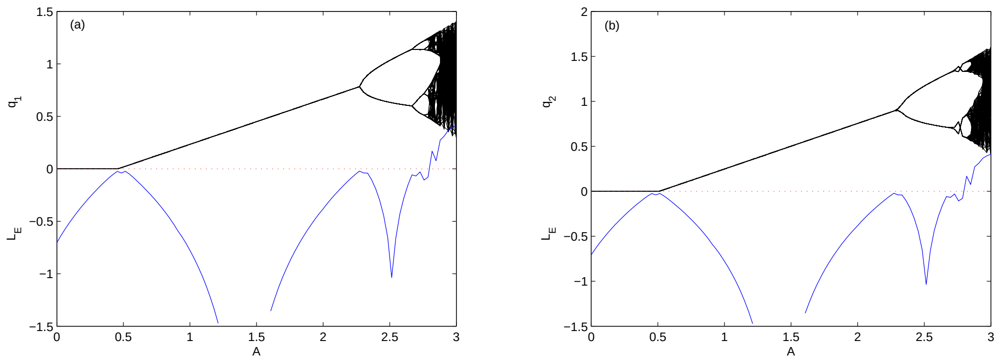


Figure 2: The bifurcation diagrams and the largest Lyapunov exponent diagrams. (a). The company 1; (b). The company 2

change of the highest electricity price A that governments allow and the largest Lyapunov exponent.

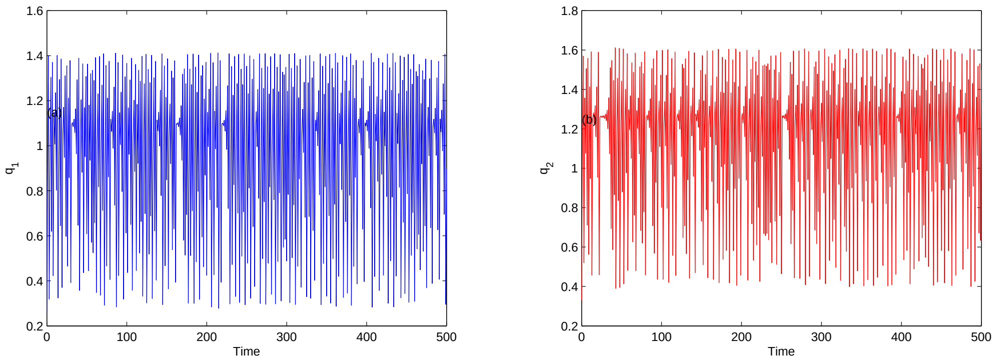
The electricity supervision departments in governments have a great influence on the stability of electricity markets. The markets will be trapped in malignant cyclic competition because of the bad supervision of government departments and so it is very necessary to make appropriate guide of electricity price for government departments. Next we will research the effects that the highest electricity price that governments set in markets has on the power generation in generation companies.

Figure 2 shows the bifurcation diagrams and the largest Lyapunov exponent diagrams. Figure 2(a) shows the change trend of the quantity of power generation in generation company 1 with the highest electricity price A that governments allow. Figure 2(b) shows the change trend of the quantity of power generation in generation company 2 with the highest electricity price A that governments allow.

We can find that q_1 and q_2 converge to the equilibrium points if $A < 2.25$ from Figure 2. This illustrates that it is beneficial to keep the electricity markets stable if the highest electricity price that governments allow is relatively small. The system will stay at the period-doubling bifurcation situation and become unstable if $2.25 < A < 2.6$. With the increasing of A, the markets will compete disorderly when the Lyapunov exponent is bigger than 0.

The game theory model on quantity of electricity produced by the two-oligopoly generation companies is a two-dimension discrete dynamic system and the system has highly complex actions when parameters take some values. Figure 3 shows the time-series diagrams of power generation in two generation companies when the system is in chaos.

We denote $A = 3, B = 0.005, b_1 = 0.46, b_2 = 0.51, c_1 = 1.15, c_2 = 0.98, \lambda_1 = \lambda_2 = \lambda$, and denote $q_1(0) = 0.26, q_2(0) = 0.33$ in Figure 3. Figure 3(a) and Figure 3(b) represent the trend diagram of power generation of generation company 1 with the change of time and the trend diagram of power generation of generation company 2 with the change of time respectively.



(a) The company 1 (b) The company 2

Figure 3: The trend diagram of power generation of generation.

Figure 3 shows that the evolution of system will become unpredictable when electricity markets are in chaos. The generation companies adjust their yield continuously in order to maximize their benefit. It is very difficult to predict the change of markets in the future for decision-makers when generation companies stay in chaotic market competition and then generation companies have difficulty in making the choice to yield because they stand in ever-changing markets.The electricity yield will stay in relatively large state of fluctuation afterwards and so it will result in the instability of markets. Finally, it will bring the bad competitive environment in markets and lead to the chaos of production, supply and marketing.

5 The control of the stability

It is certain to hope to take effective actions to keep the markets stable and guide the development of marketing economy to prevent from being trapped in chaos through fierce battle for generation companies because of the uncertainty chaotic motion possesses. The chaos in system can be restrained by changing the actions of generation companies or making appropriate price tactics by the electricity supervision departments in governments in reality. We control the bifurcation and chaotic absorption phenomenon in the dynamic system of game in two-oligopoly power generation through two ways next. We study that generation companies adjust the speed of power generation firstly and then research the effects that marketing electricity price that government departments control has on the electricity markets. Some theoretical basis can be provided for generation companies in deciding the yield and government markers in deciding the price through these two adjusting ways.

The generation companies will stay in chaos because of the competition and incorrect judgment of electricity demand, it is very disadvantageous for generation companies and markets. The chaos of yield is caused by the too fast adjusting speed in enterprises and so the electricity markets in chaos can be controlled through slowing the speed of adjusting the yield in generation companies effectively.

We denote $A = 3, B = 0.005, b_1 = 0.46, b_2 = 0.51, c_1 = 1.15, c_2 = 0.98, \lambda_1 = 0.6, \lambda_2 = 0.7$, and denote $q_1(0) = 0.26, q_2(0) = 0.33$ in Figure 4. Figure 4 (a) and Figure 4 (b) represent the trend diagram of power generation of generation company 1 with the change of time and the trend diagram of power generation of generation company 2 with the change of time respectively.

The disorderly phenomenon will disappear in markets if the speed of power generation $\lambda < 0.77$ in Figure 1. Figure 4 shows the evolution figures of quantity of power generation with the change of time in two generation companies respectively if $\lambda_1 = 0.6, \lambda_2 = 0.7$. The evolution in system can be predicted when the adjusting speed of power generation in generation companies is relatively slow and the respective quantity of power generation will be stable at the Nash equilibrium point after a period of game in Figure 4.

We denote $A = 3, B = 0.005, b_1 = 0.46, b_2 = 0.51, c_1 = 1.15, c_2 = 0.98, \lambda_1 = \lambda_2 = 1.1$, and denote $q_1(0) = 0.26, q_2(0) = 0.33$ in Figure 5. Figure 5 (a) and Figure 5 (b) represent the trend diagram of power generation of generation company 1 with the change of time and the trend diagram of power generation of generation company 2 with the change of time respectively.

A stable electricity market can be established if the government supervises and controls the electricity price appro-

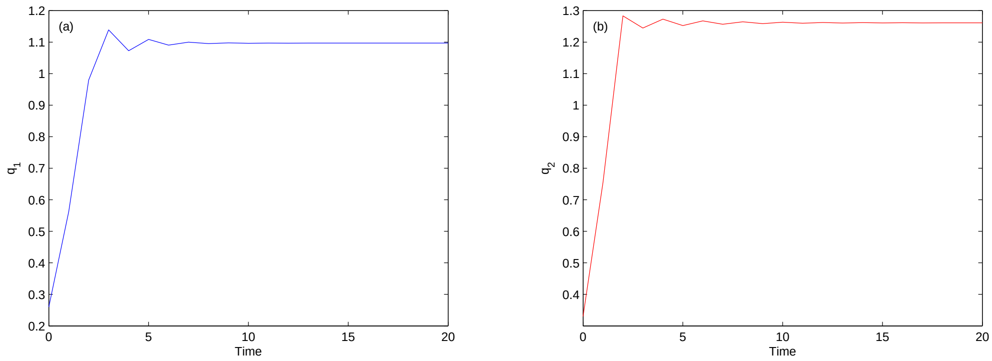
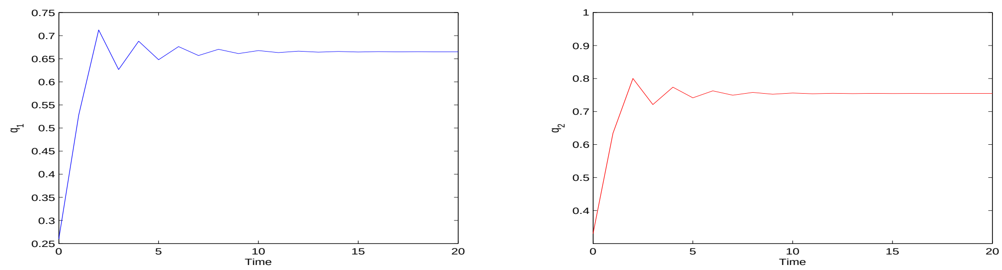


Figure 4: The trend diagram of power generation of generation. (a). The company 1; (b). The company 2.



(a) The company 1 (b) The company 2

Figure 5: The trend diagram of power generation of generation.

priately. The government markers should use the policy of adjusting electricity price correctly to optimize the whole electricity price and it will make contributions to the harmonious development of national economy and society. The disorderly phenomenon will disappear in markets when government supervision departments make an upper line for electricity price, that is $A < 2.3$ in Figure 2. Figure 5 shows the evolution figures of quantity of power generation with the change of time in two generation companies respectively if $A = 2$. The respective quantity of power generation will be stable at the Nash equilibrium point after a period of game when the upper line of electricity price that government supervision departments make is relatively low in Figure 5.

6 Discussion

This paper studies the game theory model on quantity of electricity produced by the two-oligopoly generation companies. The Nash-Cournot equilibrium point is obtained by analyzing the model of power generation we build. The quantity of power generation in generation companies will be stable at equilibrium points through the process generation companies adjust their quantity of power generation continuously in finite games although the initial quantity of power generation is different in generation companies at stable equilibrium points. However, the unstable equilibrium points indicate that the stability of equilibrium points have been destroyed. Then the system will appear the bifurcation phenomenon possibly, even evolve into chaos state and the markets will compete disorderly.

The competition between generation companies in markets will stay in chaos easily if the speed of adjusting the quantity of power generation of the generation companies or the highest electricity price that the governments allow is relatively big by analyzing the model. The appearance of chaos makes the electricity markets unstable and hurts the interests of generation companies. So, chaos will destroy the markets and generation companies seriously. The chaos is harmful to the healthy development of markets at the same time. Hence, the generation companies and governments need to take effective action to prevent the chaos for electric supervision departments.

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