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Dynamic Control of Proclivity toward Selling Electricity Using Persuasive Dialogue System

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Abstract: This paper proposes an electricity market model comprising farm owners, an electricity company, and a persuasive dialogue system, to dynamically adjust electricity price by controlling owners' proclivity toward selling their electricity. Several numerical examples confirm that the proposed model facilitates price adjustment.

Key Words: electricity price, electricity market, persuasive dialogue system, feedback control.

1. Introduction

Electricity is one of the most important forms of energy in our life. Recently, the electricity consumption and the cost of electricity generation have been rising. Hence, efficient use and generation of electric energy are important. From the viewpoint of efficient use, smart grid control methods, including those for green electricity, wind or solar power, have been proposed [1],[2]. These methods cover the so-called demand-side management in a smart grid [3]. From the viewpoint of efficient generation, a dispatch and pricing method has been proposed to avoid the risk of power imbalance from the electricity company side [4]. However, achieving efficient generator use is not easy because electricity demand changes temporally and estimating the demand accurately is difficult in general. In a day, there is a peak period and an off-peak period. To ensure stable supply at all times, electricity companies incur considerable cost to maintain these facilities. Therefore, the number of non-operational facilities during the off-peak period should be decreased to the extent possible.

To achieve this, methods of demand response [5]–[9] or selling electricity [10],[11] have been considered. Demand response aims to persuade consumers to change their consumption patterns to reduce the demand gap between the peak and off-peak periods, in order to ensure stable supply. To this end, the company might raise electricity price by using strategies such as Real-Time Pricing and Time of Use [8] or incentivize consumers who cooperate by reducing consumption when the electricity gap is not balanced. When such a method works successfully, the electricity demand throughout a day is expected to be flat. This would lead to the reasonable reduction in the number of facilities necessary in peak periods and the cost of maintaining non-operational facilities in off-peak periods.

The electricity company is obligated to fill the electricity demand-supply gap in the peak period, by employing a strategy of buying electricity from people or organizations who store it; for example, people own solar power plants or energy storage facilities. A method for improving wind farm dispatch in the electricity market has been proposed [10]. In [11], demand response and electricity selling are employed to achieve cost-comfort balancing. These studies focus on the viewpoints of people or organizations who sell the electricity. However, in this study we consider the electricity company's viewpoint. We call the people who store electricity as farm owners. They have adequate electricity, and the electricity company can purchase it to compensate for electricity shortage.

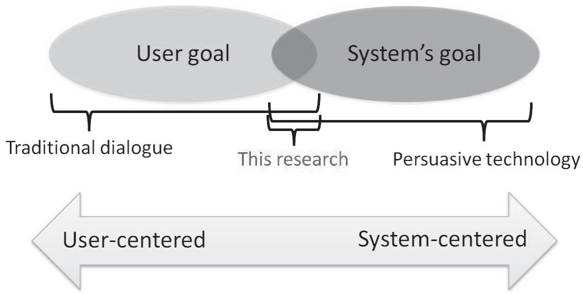

Fig. 1 Categorization of dialogue systems [12].

Consider a situation where electricity selling occurs in the peak period. When the electricity company buys small amounts of electricity from the farm owners, the electricity price should rise because the price depends on quantity. Then, it is assumed that the electricity company can use a persuasive dialogue system to negotiate purchase prices with the farm owners. Hence, we consider an electricity market that includes a persuasive dialogue system.

In the literature [12], a persuasive dialogue system and scheme for categorizing dialogue systems based on goals to be achieved have been proposed, as shown in Fig. 1. The ellipse on the left side denotes user's goals that a dialogue system can achieve. For example, the dialogue system provides information useful to the user [13] and allows the user to communicate with the system via chats [14]. The ellipse on the right side denotes system's goals that a persuasive system can achieve; for example, devising a promotion system to sell products. The common area between both the ellipses represents a persuasive dialogue system, which tries to achieve both user and system goals by leading the user. As an example of such a system, there is an advisory system which helps a student select the best laboratory based on his/her requirements [12]. In this study, we use

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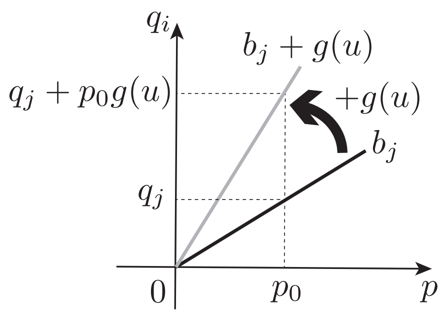

Fig. 2 Effect on the farm owner's proclivity toward selling the electricity by the persuasive dialogue system.

the persuasive dialogue system (the common area in Fig. 1) to negotiate with the farm owners. The attempt of introducing the persuasive dialogue system into the electricity market to change the farm owner's proclivity (decision making) is novel. Hence, the purpose is to investigate what the novel concept produces. Here, we assume that the persuasive dialogue system enables to change the farm owners' proclivity.

This paper proposes an electricity market model with a persuasive dialogue system. An electricity market model without a persuasive dialogue system has been presented in [15]. In the model proposed herein, the company manages the parameters of the persuasive dialogue system, which is installed in the premiss of all farm owners. The dialogue system is to serve the purpose of changing farm owners' proclivity toward selling, which allows the company to balance the demand-supply gap. The results of numerical experiments based on the proposed method confirm that the model enables the company to track the electricity price to a desired price by using the persuasive dialogue system.

2. Controlled Object

The controlled object is an electricity market including the persuasive dialogue system, as stated below.

2.1 Persuasive Dialogue System for Electricity Pricing

We consider a situation where an electricity company needs to compensate for electricity shortage and farm owners have enough electricity to sell to the electricity company. In this situation, we assume that the electricity company buys electricity from the farm owners and that the price of such electricity depends solely on the amount of electricity bought. The amount is decided by the farm owners' proclivity toward selling their electricity. Proclivity refers to the level to which they are willing to sell electricity to the electricity company. If the farm owners' proclivity is low and the amount of electricity sold by them to the electricity company is small, the electricity price rises. In short, the electricity price depends on the farm owners' proclivity to sell.

However, the electricity company would prefer avoiding hikes in the electricity price and control the electricity price to avoid increasing the cost. To this end, the company must manage to persuade the farm owners to increase the amount of electricity they sell. Negotiation with the farm owners to increase their proclivity toward selling their electricity to the company is one of the ways to achieve the goals.

The persuasive dialogue system is introduced into each farm owner's house to facilitate negotiations. The following three conditions are assumed in this study. First, each farm owner determines the amount they want to sell, based solely on the proclivity toward selling electricity. Second, there exists a linear relationship between the amount of electricity sold by the farm owners, q_i, and the electricity price, p. The inclination of this linear line is defined as a proclivity, b_i, and the relationship is written as $q_i = b_i p$. Third, the effect of the persuasive dialogue on the farm owners' proclivity is expressed quantitatively. A real proclivity would be more complex; for example, no farm owner would sell the electricity to the company unless the unit price exceeds some standard. However, we assume that the linear relationship exists in the appropriate vicinity. Hence, the electricity company might deliberately not decrease the electricity price in this model. Figure 2 shows the linear relationship between the amount of electricity, q_i, which the farm owners sell to the company, and the electricity price, p. The black line's inclination represents the j-th farm owner's proclivity toward selling their electricity without applying the persuasive dialogue system, b_j. In contrast, the inclination of the gray line represents the farm owners' proclivity toward selling their electricity when subjected to the persuasive dialogue system, $b_j + g(u)$. An increase in the proclivity yields a greater amount of electricity, $q_j + p_0 g(u)$, which leads to a decrease in the price. Accordingly, the desired price is achieved by controlling the farm owners' proclivity. In addition, two scenarios for acceptance to negotiation are assumed. In the first scenario, it is assumed that farm owners always accept negotiation from the persuasive dialogue system. In the second scenario, it is assumed that they accept negotiation from the system probabilistically. Such behavior is written with a Bernoulli process, as will be explained in Section 2.2.

2.2 Electricity Market Model

The electricity market is composed of n farm owners, the electricity company and the persuasive dialogue system. The farm owners have enough electricity to sell to the electricity company. The electricity company does not have enough electricity to supply to the consumers and needs to buy the electricity from the farm owners to compensate for the shortage.

The entire model is shown in Fig. 3. The electricity company buys the electricity from the farm owners, and in exchange pays a set price to the farm owners. The price depends on the farm owners' proclivity toward selling their electricity. However, the electricity company would like to control the electricity price to keep the procurement cost down. When the electricity company introduces the persuasive dialogue system, it is able to buy electricity close to the desired price. The effect of persuasive dialogue is adjusted by the company.

The electricity market model is formulated as the following optimization problem:

$$\max_{q \geq 0} \quad \sum_{i=1}^{n} -C_i(q_i - pg(u)\omega_i), \tag{1a}$$

$$\text{s.t.} \quad \sum_{i=1}^{n} (q_i - pg(u)\omega_i) = d, \tag{1b}$$

where $C_i(x)$ is the i-th farm owner's cost function, which is assumed to be convex in x, q_i is the amount of electricity that can be sold by the i-th farm owner, q is the vector consisting of q_i, p is the unit price of electricity, u is an input into the persuasive

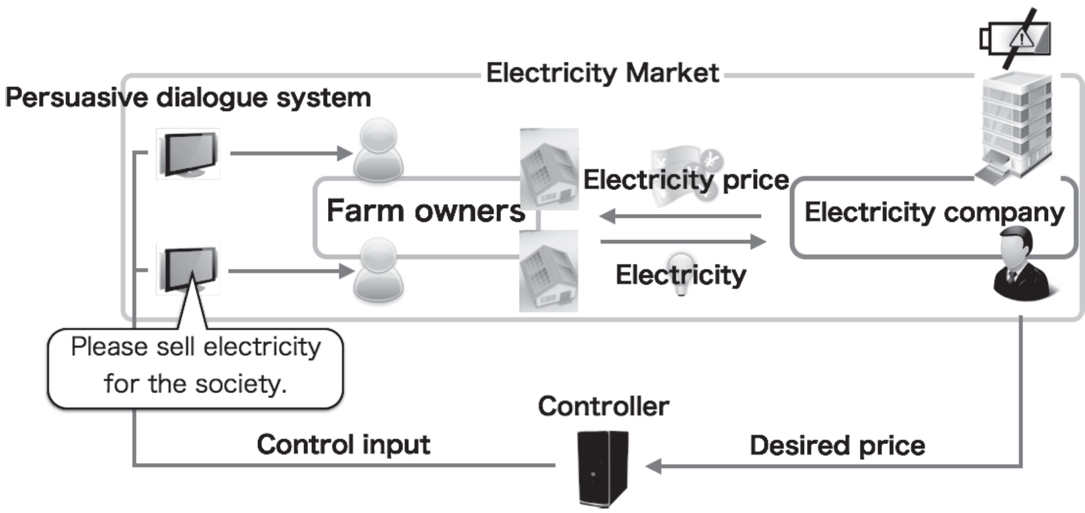

Fig. 3 Outline block diagram of whole model.

dialogue system, $g(u)$ is the effect of persuasive dialogue on farm owners' proclivity toward selling electricity, $pg(u)$ is the increase in the amount of electricity sold on account if the farm owners accept the negotiation, and ω_i is a function taking 0 or 1 based on the given probability according to the following:

$$\omega_i = \begin{cases} 1 \text{ with probability } s, \\ 0 \text{ with probability } 1 - s, \end{cases} \tag{2}$$

where d denotes the demand-supply gap. For a given electricity price p, each farm owner has the proclivity toward selling electricity b_i and decides the amount of electricity to sell q_i to maximizes his/her evaluation function. Hence, the decision variable in the problem (1) is q.

The optimization problem (1) consists of each farm owner's decision making and the electricity company's equality constraint, as described in the following paragraphs.

2.2.1 Farm owner model

It is assumed that the farm owners have enough electricity to sell to the electricity company, and two scenarios are considered for the farm owners' property. In the first scenario, they always accept negotiation from the persuasive dialogue system ($\omega_i = 1$), while in the second scenario, they accept negotiation from the system probabilistically ($\omega_i = 1$ with probability $s, \omega_i = 0$ with probability $1 - s$). We consider that each farm owner decides the quantity of electricity he/she wants to sell to maximize his/her evaluation function. The amount of electricity sold, q_i, is the solution to the following optimization problem:

$$\max_{q_i \geq 0} \quad p(q_i(b_i, p) - pg(u)\omega_i) - C_i(q_i(b_i, p) - pg(u)\omega_i), \tag{3}$$

where b_i denotes the farm owner i's proclivity toward selling electricity. Summarizing all of farm owners' evaluation function in the market with the respect to i, we have the following:

$$\max_{q \geq 0} \quad pd - \sum_{i=1}^{n} C_i(q_i - pg(u)\omega_i),$$

where pd is independent of the decision variable, and the evaluation function of the electricity market is given by (1a).

2.2.2 Electricity company model

The electricity company only has the facility to supply electricity to consumers in the off-peak period. However, the company must maintain balance between electricity demand and supply. To this end, the total amount of electricity purchased from the farm owners must coincide with the amount of electricity shortage. The condition that the company must achieve is as follows:

$$\sum_{i=1}^{n} (q_i(b_i, p) - pg(u)\omega_i) = d, \tag{4}$$

and the equation is satisfied when its solution is the equilibrium point of the optimization problem. The equality constraint (1b) is given by (4). From the above, we can formulate the entire electricity market by (1).

3. Numerical Calculation Method

3.1 Optimal Condition of Solutions

This section states the optimal condition for (1), which is equal to that for (3). Since the objective function of (3) is convex in q_i, the following optimal condition holds:

$$\dot{C}_i(q_i^*(b_i, p) - pg(u)\omega_i) - p = 0 \; \forall q_i \; \forall i, \tag{5}$$

where $\dot{C}_i(b_i) = \dfrac{dC_i(b_i)}{db_i}$, and q_i^* denotes the optimal solution to the optimization problem (3). Noting $q_i \geq 0$, the optimization (3) can be transformed into the following:

$$\begin{aligned} q_i^* &= \arg\max_{q_i \geq 0} \quad p(q_i - pg(u)\omega_i) - C_i(q_i - pg(u)\omega_i), \\ &= \max(\{0\} \cup \{q_i | \dot{C}_i(q_i - pg(u)\omega_i) = p\}), \\ &= [(\dot{C}_i)^{-1}(p) + pg(u)\omega_i]^+, \end{aligned} \tag{6}$$

where $[a]^+$ is the function that returns 0 if $a < 0$, and a otherwise.

3.2 Numerical Solution to the Optimization Problem

We use the dual gradient algorithm [15],[16] to solve the optimization problem (1). First, to update the electricity price, the following equation is expressed in the k-th iteration by using (1b).

$$p(k+1) = \left[p(k) - \gamma \left(\sum_{i=1}^{n} (b_i(k) - g(u)\omega_i(t))p(k) - d \right) \right]^+, \tag{7}$$

where γ indicates the step size, which affects the electricity price convergence speed. t is a time step in a control loop. Second, (6) is transformed considering each farm owner's proclivity toward selling energy b_i. In the k-th iteration, proclivity $b_i(k)$ is described as follows.

$$b_i(k) = \left[\frac{\left(\dot{C}_i\right)^{-1} (p(k))}{p(k)} + g(u)\omega_i(t) \right]^+. \tag{8}$$

This is the update of the proclivity. Finally, because we calculate (7) and (8), the optimal solution $q_i^* = b_i(k)p(k)\ \forall i$ is obtained when $p(k+1) = p(k)$ is satisfied.

4. Feedback Control

We use a PI controller so that the electricity price converges to the desired price $\overline{p}$. The controlled object is the entire electricity market, including the persuasive dialogue system. The aforementioned PI controller takes the error of the electricity price as an input.

To ensure that the electricity price converges to the desired price, the persuasive dialogue system must change the farm owners' proclivity toward selling the electricity at an appropriate price. The effect on the persuasive dialogue system on proclivity $g(u)$ is defined as $-u$, that is, $g(u) := -u$. $u(t)$ at step t is given by the following:

$$u(t) = K_P(\overline{p} - p_{out}(t)) + K_I \sum_{i=0}^{t} (\overline{p} - p_{out}(i)),$$

where $\overline{p}$ is the desired price, p_{out} is the price when $p(k+1) = p(k)$ holds at step t, and K_P and K_I denote the proportional and integral gains, respectively. Actually, the effect of the persuasive dialogue system on proclivity is more complex, but we consider the fundamental case. An overview of the algorithm including the PI controller is shown in Table 1. A block diagram of the entire system is drawn in Fig. 4, where b_i indicates each farm owner. The broken line in the figure shows the controlled object. Especially, the persuasive dialogue system works as a kind of actuator for controlling the farm owners' proclivity.

5. Numerical Simulation Results

To confirm whether the electricity price converges to the desired price, we perform a numerical simulation in four scenarios.

In the first scenario, the electricity company does not use the persuasive dialogue system. In the second scenario, the electricity company is assumed to know all farm owners' cost functions and to use the persuasive dialogue system. The farm owners always accept the negotiation. The i-th farm owner's cost function is expressed in $C_i\ \forall i$. In the third scenario, it is assumed that the electricity company does not exactly know the farm owners' cost functions. In other words, the farm owners' cost functions that the company knows, include modeling errors. The company uses the persuasive dialogue system and the farm owners always accepts negotiation. In the forth scenario, the electricity company uses the persuasive dialogue system with modeling errors in the situation where the farm owners

Table 1 Algorithm for computing the electricity market model.

Algorithm1 Calculate $b_1, b_2, ..., b_n, p$
Set: $d, \gamma, p(0), \overline{p}, K_P, K_I$
1. while $p \neq \overline{p}$
2. while $d \neq Q$
3. $b_i(k) \leftarrow \left[\frac{\left(\dot{C}_i\right)^{-1} (p(k))}{p(k)} + g(u)\omega_i(k) \right]^+$
4. $p(k+1) \leftarrow \left[p(k) - \gamma \left(\sum_{i=1}^{n} (b_i(k) - g(u)\omega_i(t))p(k) - d \right) \right]^+$
5. $Q \leftarrow \sum_{i=1}^{n} b_i(k)p(k)$
6. $k \leftarrow k+1$
7. end while
8. $p_{out}(t) \leftarrow p(k)$
9. $u(t) \leftarrow K_P(\overline{p} - p_{out}(t)) + K_I \sum_{i=1}^{t} (\overline{p} - p_{out}(i))$
10. $g(u) \leftarrow -u$
11. $t \leftarrow t+1$
12. end while

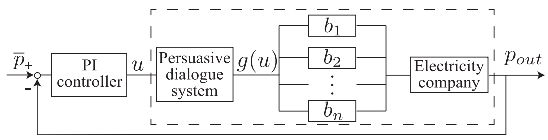

Fig. 4 Block diagram of the electricity market system.

accept negotiation probabilistically. In all scenarios, there are 10 farm owners in total, and their cost functions are expressed as follows:

$$C_i = 0.1x^4,\ i = 1, 2, 3, \tag{9a}$$
$$C_i = 0.2x^4,\ i = 4, 5, 6, \tag{9b}$$
$$C_i = 0.15x^4,\ i = 7, 8, 9, 10. \tag{9c}$$

The initial electricity price $p(0)$ is 32, and the desired price $\overline{p}$ is 28. The shortage amount of electricity d is 40. The step size γ is 0.05. The effect of persuasive dialogue is $g(u) = -u$. The PI controller gains are set to $K_P = K_I = 1.0 \times 10^{-4}$. MATLAB 2015a was used for the numerical simulation.

The first scenario in which the electricity company does not introduce the persuasive dialogue system into the electricity market is considered. The solution is obtained by solving the optimization problem (1) with $g(u) = 0$. The result is shown in Fig. 5. The figure shows the process of finding the optimal solutions. Figure 5 a) expresses a control input into the persuasive dialogue system. Figure 5 b) shows that the electricity price p converges to 36.6162. Figure 5 c) illustrates the lack of the amount of the electricity. Figure 5 d) expresses the farm owners' proclivity toward selling energy. These results indicate that the electricity price should be 36.6162 to compensate for the electricity shortage, the amount of which is 40.

The second scenario is where the electricity company knows the farm owners' cost functions C_i (9) correctly. Moreover, it introduces the persuasive dialogue system into the electricity market, and the farm owners always accept negotiation. The feedback control is applied to the system. If the following inequalities hold, then the equality constraint (1b) can be satisfied.

$$-\epsilon \leq \sum_{i=1}^{n} (q_i(b_i, p) - pg(u)\omega_i) - d \leq \epsilon, \tag{10}$$

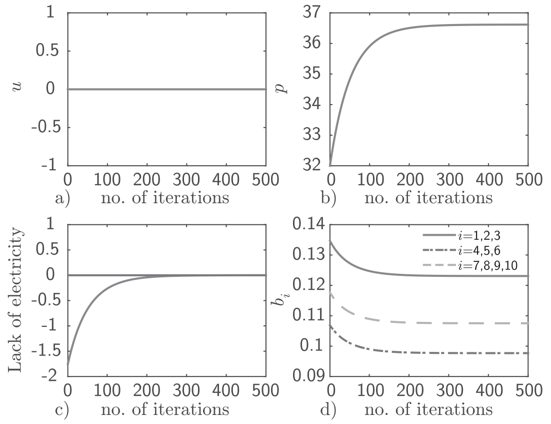

Fig. 5 Deterministic simulation result with no controlling.

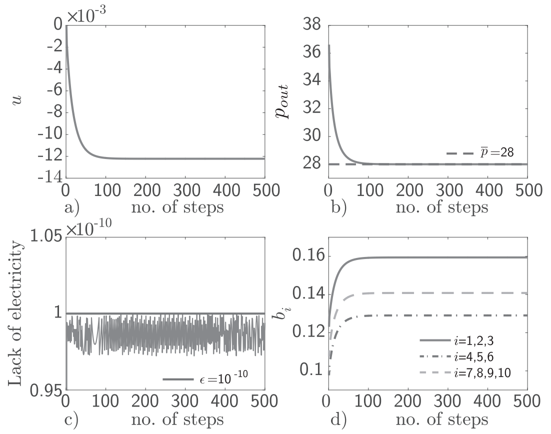

Fig. 6 Deterministic simulation result with correct modeling.

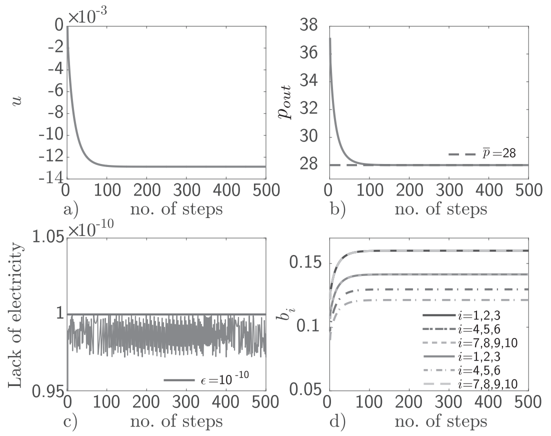

Fig. 7 Deterministic simulation result with modeling error.

where $\epsilon = 10^{-10}$. The result is shown in Fig. 6. Figure 6 c) expresses the values near the upper bound in (10). Figure 6 b) shows that the electricity price decreases and converges to the desired electricity price 28. As the price decreases, the farm owners' proclivity toward selling energy b_i increases by the effect of the persuasive dialogue. Therefore, controlling the farm owners' proclivity makes the price converge to the desired price in electricity market with the persuasive dialogue system.

The third scenario where the electricity company does not exactly know the farm owners' cost functions (9) and where the farm owners always accept negotiation. The electricity company considers the following equations as the farm owners' cost functions:

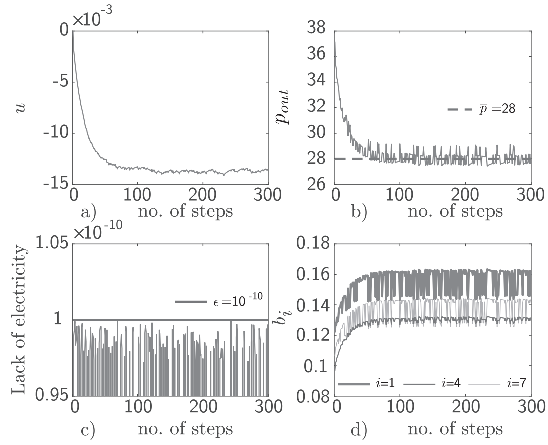

Fig. 8 Probabilistic simulation result with modeling error (2 farm owners, 70%).

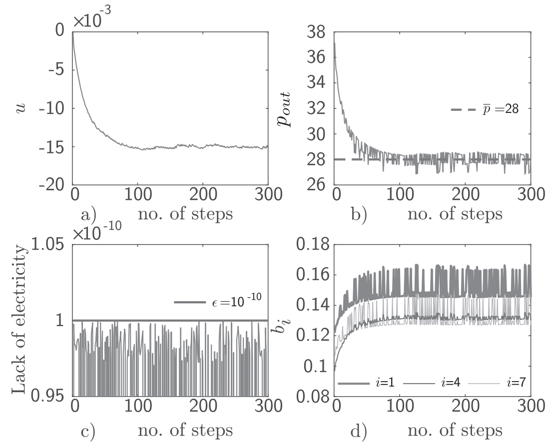

Fig. 9 Probabilistic simulation result with modeling error (2 farm owners, 30%).

$$C_i = 0.15x^4,\ i = 1, 2, 3, \tag{11a}$$

$$C_i = 0.25x^4,\ i = 4, 5, 6, \tag{11b}$$

$$C_i = 0.1x^4,\ i = 7, 8, 9, 10, \tag{11c}$$

which are different from the correct equations (9). The result is shown in Fig. 7. Figure 7 b) indicates that the electricity price, p_{out}, converges to the desired electricity price 28. Therefore, the feedback control system is robust against the modeling errors in the cost functions.

The fourth scenario that the electricity company uses the persuasive dialogue system with modeling error in the situation where the farm owners probabilistically accept negotiation is analyzed. In this scenario, four patterns are considered. Two farm owners accept negotiation (the other eight always accept negotiation) at 70% and 30% (s = 0.7 and 0.3 in (2)), and eight farm owner accept negotiation (the other two always accept negotiation) at 70% and 30%(s = 0.7 and 0.3 in (2)). The other parameters are the same as those in the third scenario. The results are shown in Figs. 8-11 and the average and the variance of the electricity price are summarized in Table 2. The average is taken in steps, which is defined as follows:

$$m = \frac{1}{1000 - 500} \sum_{t=501}^{1000} p_{out}(t),$$

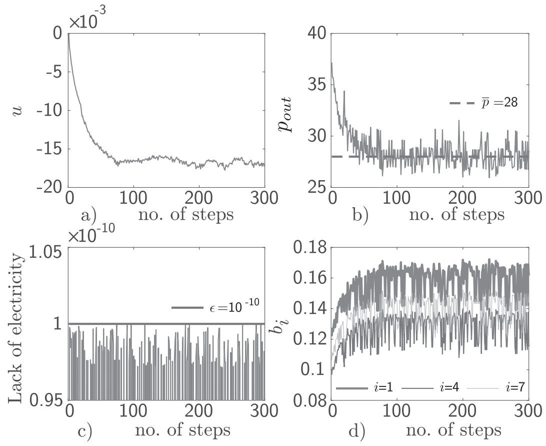

Fig. 10 Probabilistic simulation result with modeling error (8 farm owners, 70%).

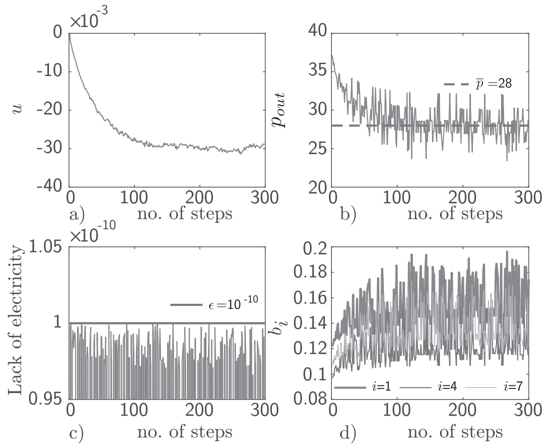

Fig. 11 Probabilistic simulation result with modeling error (8 farm owners, 30%).

Table 2 Average and variance of electricity price.

Situation	Average price	Variance in desired price
Deterministic case	28	0
2 people, 70%	28.0035	0.2015
2 people, 30%	27.9974	0.2432
8 people, 70%	28.0111	1.4170
8 people, 30%	27.9941	3.3565

where m is the average price. The variance in the desired price indicates the variance from the desired price, and is assumed that the electricity prices after time step 501 is in steady-state. It is calculated by the following equation:

$$\begin{aligned} V' = \sum_{t=501}^{1000} (p_{out}(t)-\overline{p})^2 &= \sum_{t=501}^{1000} \{(p_{out}(t)-m)-(\overline{p}-m)\}^2 , \\ &= \sum_{t=501}^{1000} (p_{out}(t)-m)^2 + 500(\overline{p}-m)^2 , \\ &= V + 500(\overline{p}-m)^2 , \end{aligned}$$

where V' is the variance from the desired price, $p_{out}(t)$ is the electricity price at step t and V is the variance from the average price. Table 2 shows that the difference between the average electricity price and the desired price ($\overline{p} = 28$) is at most on the order of 10^{-2}. It would be appropriate to consider that each electricity price converges to the desired price in terms of the average. However, the variance in the desired price increases gradually as the uncertainty increases. The uncertainty also increases when the number of farm owners who probabilistically accept negotiation increases and the probability of accepting negotiation decreases.

6. Conclusion

In this paper, we proposed an electricity market model that can set a desired electricity price for an electricity company by using a persuasive dialogue system with a feedback control. The results of the numerical experiments confirmed that the electricity price converged to the desired price, even if the electricity company had no precise information about the farm owners' cost functions. In addition, even when the farm owners probabilistically accepted negotiation via the persuasive dialogue system, the average electricity price converged to the desired price.

In the future, we will attempt to prove that the electricity price converges stably to some value.

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