A Practical Method for Realizing Large-scale and Flexible Demand Response

Toshitsugu Gunji
Graduate School of Engineering
Tohoku University
6-6, Aramaki Aza Aoba, Aoba-ku,
Sendai, Miyagi, 980-8579, Japan
Email: gt2099@iic.ecei.tohoku.ac.jp

Yoshihiro Sugaya
Graduate School of Engineering
Tohoku University
Email: sugaya@iic.ecei.tohoku.ac.jp

Shinichiro Omachi
Graduate School of Engineering
Tohoku University
Email: machi@ecei.tohoku.ac.jp

***Abstract*—Electric power is one of the important infrastructures for our life. The electric power system is going to be changed dramatically by clean energy, which includes unstable power supplies such as photovoltaics and wind-power generation, and by introduction of distributed power generation. In order to maintain a balance between supply and demand, a mechanism called demand response, which manages user consumption of electricity depending on supply conditions at peak time, becomes the focus of attention. In this paper, we conducted research on the demand response. Since the number of electric-power users is immense, the management system will require large computation time to account for every user's request. In order to flexibly perform the demand response, we propose a method to break a large-scale problem into smaller-scaler problems to reduce computation time. We solve these small problems using a system with hierarchical structure for reducing computation time and for overall optimization. In this paper, we adopt and creatively use the reservation trade method and a brown-out optimization method for shift and reduction of demand, and we conduct experiments using computer simulations to confirm the effectiveness of our approach. We show that the proposed system can reduce computation time for a large-scale demand response.**

I. Introduction

Energy from electric power is one of the most important necessities for daily life. Therefore, stable management of the electric system is imperative. For this reason, electric power companies must possess excess generating capacity to cope with the balance between supply and demand. Therefore, a mechanism called demand response, which manages user consumption of electricity depending on supply conditions at peak time, becomes the focus of attention.

The electric power company communicates with each user via an electric power meter known as a smart meter. The power company monitors electricity demand in real time and execute a demand response via the smart meter.

Electric power companies have some general problems. First, it is not economical to have a large gap between the maximum and minimum demand. Therefore, the power company must have excess generating capacity to cope with the balance between supply and demand.

In Japan, this balance between supply and demand has been tight since the Tohoku earthquake of March 11, 2011, and the subsequent shortage of electricity-generating capacity due to the shutdown of nuclear power plants. In a worst-case scenario, extensive power blackouts may occur. Electric power companies can not quickly increase the generating capacity to address the balance between supply and demand, because a large amount of time is required to construct power plants.

The number of clean-energy systems, such as photovoltaics and wind-power generation, has increased in recent years due to the need for energy security and greenhouse gas reduction [2]. In order to control the energy supply according to rapid changes in demand for electricity, an electric power company must have sufficient reserve power and battery storage because production of clean energy is unstable.

Demand response is an advantageous way of coping with these problems. The electric power company can reduce reserve power, storage, and the construction of power plants by introducing demand response.

Various systems of demand response have been proposed. A system called RTP (Real Time Pricing) [4][5][6], which changes the electricity price in real time according to demand, is used in the United States. Other methods of changing the electricity price, including CPP (Critical Peak Price) and TOU (Time of Use) [4], are available. However, when two or more power supplies are controlled, it is difficult to forecast future electricity demand correctly by methods such as changing the price of electricity. Although a way that power companies directly control customers' appliances was proposed [4], this method has drawbacks in which quality of life deteriorates and load on the control side becomes large.

In the paper, we propose a system for performing efficient power management with user flexibility. The reservation trade method and the optimization of power saving are considered as a system of demand response.

With a reservation trade method, one reserves a time slot to use an appliance in advance. This method gives merit to the user who makes a reservation earlier. For this reason, electricity demand scheduling will be planned stably in an early stage. In conjunction with this practice, electricity demand will be reduced by optimizing power savings.

However, it is thought that the load on the control side would become large under this method; this is because the number of Japanese households involved in the demand response would be huge (e.g., Kanto area: 17.1 million households; Chukyo area: 3.8 million households; Kinki area: 9.1 million households [7]). If the power company provides service to all of the households, the calculation load is high. Therefore, we divide this large-scale problem into small problems that are solved using a distributed processing of hierarchical structure that is applied in some fields [8]. We construct a flexible system that makes a large-scale-demand response possible.

II. Proposed Method

This section presents our proposed method. First, we judge whether current scheduled demand is larger than a restriction in peak power. When the current power consumption schedule is larger than the restriction in peak power, the user must reduce demand. We divided one day into 48 time slots, each of which had 30 minutes. The proposed method constructs the electricity demand schedule for one entire day at the beginning of the day, and updates the schedule every 30 minutes.

A. Demand-reduction algorithm

Demand response is applied to washing machines, water heaters, and air conditioners. Power consumption of refrigerators and IH cooking stoves are taken into account, but they are not controlled by the demand response. As a method of demand response, the reservation trade method is adopted for washing machines because the operating time slot of the washing machine tends to be short and it is easier to shift this operating time slot than it is for other household appliances.

In addition, optimization of the amount of power savings is applied to air conditioners and water heaters because these appliances are used for long durations, and even if their use is prevented or reduced for only a short time, it has little impact on the quality of life.

Let $P_{all}(t), t = t_p, ..., 48$ be the total power consumption by all users and let $P_r(t)$ be the restriction in peak power, where t_p indicates the current time slot. The procedure of the proposed system is given as follows:

1) Repeat for every 30 minutes.
   a) If there is t such that $P_{all}(t) > P_r(t)$ then
      i) Execute the reservation trade method for washing machines.
      ii) Calculate the amount of required power-saving $\boldsymbol{D} = D(t_p), ..., D(48)$ as follows at each time slot,

$$\boldsymbol{D} = \boldsymbol{P}_{all} - \boldsymbol{P}_r. \quad (1)$$

      iii) Execute optimization of the amount of power saving for air-conditioners.
      iv) Calculate the remaining amount of required power-saving $\boldsymbol{D}$.
      v) Execute optimization of the amount of power saving for water-heaters.

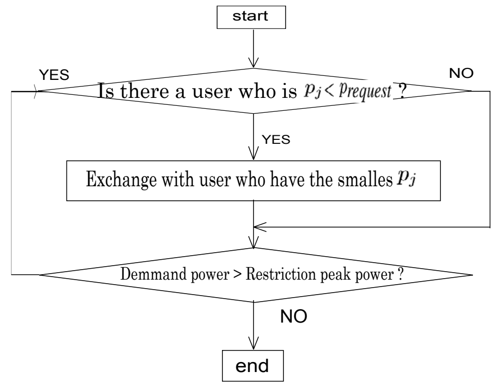

Fig. 1. Reservation trade method

1) Reservation trade method: The reservation trade method is a method in which a user who reserves an appliance-use time slot early can obtain an advantage. Users who make reservations late may be suspended because total power consumption is deliberately restricted by the power company. If a suspended user wants to use the appliance, he or she must buy a reservation for a time slot by exchanging points.

A !HPoint !Is a kind of virtual money, that is used in some loyalty programs. For example, we assume that the user can obtain points according to the amount of power consumption and the amount of power savings, and these points can be used for payment of an electricity bill or for exchange with goods and green energy. Therefore, electric power companies can promote electricity and power saving by implementing ideas such as the point system.

The point system is used when we judge whether users purchase reservations from other users. Let $p_i, i = 1, ..., N(\textit{the number of users})$ be the desired points of user i and $p_{request}$ be the permission-point of user i. The flow chart for the algorithm of the reservation trade method is shown in Fig.1. The reservation trade method is applied as follows:

1) Users reserve operating time slots for their appliances.
2) Repeat until satisfying termination condition is reached.
   a) A suspended user i searches for users who have made successful reservations and have p_j smaller than $p_{request}$.
   b) Select the user who has the smallest p_j from these users.
   c) The user i negotiates with the user who has the smallest p_j.
   d) When the negotiation is successful, users i and j exchange the reservation and points.

The termination condition is defined as power demand falling below the restriction in peak power, or there are no users available who can exchange the reservation.

In this paper, the reservation trade method is applied to washing machines. A user who reserves a washing machine early can use electricity advantageously. Consequently, many users will tend to make reservations early, and it becomes easy for the power company to plan efficient power management.

2) Optimization of the amount of power saving: Optimization of the amount of power saving is a method that optimizes the amount of power saving for efficient power management with user flexibility. This method is applied to an air-conditioner and a water heater.

Let $\boldsymbol{d_i}, i = 1, ...N(\textit{the number of users})$ be power-saving rate, $\boldsymbol{s_i}$ be the user's power desired schedule, which the user initially planned, and $\boldsymbol{x_i}$ be user's actual power schedule. This method searches for an optimal $d_i(t), i = 1, ...N$ for $D(t)$ with user's flexibility. First, this method is applied for the air conditioner, using the following procedure.

1) At the start of the day, $\boldsymbol{x_i}$ is initialized

$$\boldsymbol{x_i} = \boldsymbol{s_i}. \tag{2}$$

2) Repeat until termination condition is satisfied.
   a) Determine $d_i(t)$ so that the function F is minimized. The function F is defined as

$$F = \left| D(t) - \Sigma_{i=1}^{N} P_i(t) \right|, \tag{3}$$

   where $P_i(t)$ is power-saving function used to judge whether the user saves power. The function $P_i(t)$ is defined as

$$P_i(t) = \begin{cases} x_i(t)d_i(t) & (R < C), \\ 0 & (R > C), \end{cases} \tag{4}$$

$$R = (s_i(t) - x_i(t)(1 - d_i(t)))/s_i(t), \tag{5}$$

   where C is power-saving coefficient that represents degree of user's, and is used to judge whether the user saves power.

3) Update $\boldsymbol{x_i}$ as follows:

$$x_i(t) = x_i(t)d_i(t). \tag{6}$$

The Genetic Algorithm (GA) is used for optimization based on the premise that we are unaware of the kind of P_i the user has. Even if the function F is very complex the GA can solve it, whereas Linear Programming(LP) can not. The termination condition is defined as the case where the value of F does not change to an improved value. Next, D is updated by subtracting the amount of power savings achieved by the method for air conditioners, and then the method is applied to water heaters. Assuming that a water heater ideally consumes 3.0 kWh of electric energy per day, the quantity of power saved must be consumed in other time slots. The procedure for a water heater similar to that for air conditioners, but Eq.(3) is replaced by F_{water}. The evaluation function F_{water} is defined as

$$F_{water} = F + A, \tag{7}$$

$$A = \Sigma_{t=1}^{48} \left| (S(t) - P_{ave}) \right|, \tag{8}$$

where $S(t), t = 1, ...48$ is power consumption of all users at time slot t, and P_{ave} is the average power used by water heater for a day.

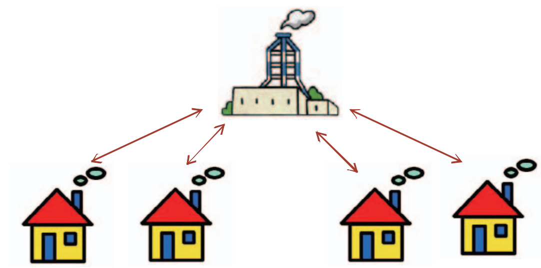

Fig. 2. Centralized system

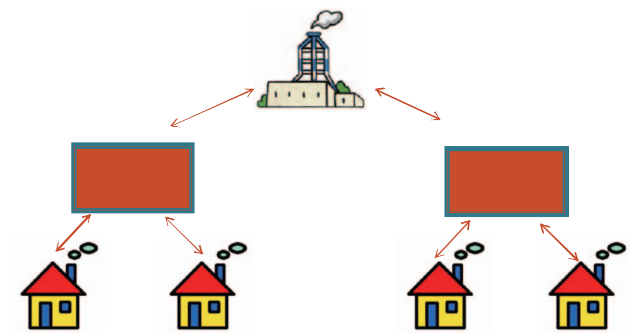

Fig. 3. Hierarchical system

B. Hierarchical distributed processing structure

The centralized system has formed a structure as shown in Fig. 2. With such structure, the system must manage all users at one location. The load of demand response on the large scale is high, and the required computing time becomes large. Therefore, we introduce the method of dividing a large-scale problem and using a hierarchical structure, as shown in Fig. 3. This method divides users into groups, in a structure consisting of three layers. Users form the bottom, and the second layers consist of leaders of the user group. A power-plant agent in the top layer manages the leaders. For this reason, the power-plant agent is able to understand and manage the entire demand. It deals with the divided problem by using this structure.

The restriction in peak power for each group is determined according to the number of users in the group. The user can execute the reservation trade method and optimize the amount of power savings only within his or her group. For this reason, we expect that computation time will be reduced, but the reduction of peak power will be different from that of the centralized system.

C. Assumptions and operations of the proposed method

In the proposed method, it is assumed that users previously input their initial plans for electric appliances, their time schedules, their conditions for the reservation trade, and their priority maps in the day into their own smart meters. The agent of the smart meters manages users' electric appliances in accordance with the day's use plans and execute demand response in accordance with the users' time schedules and conditions.

An example of the initial plan of a user's power usage is

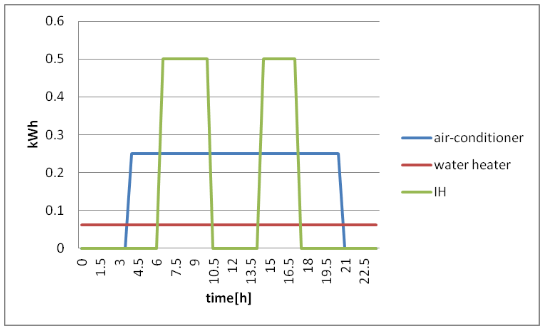

Fig. 4. Initial plan of home appliances

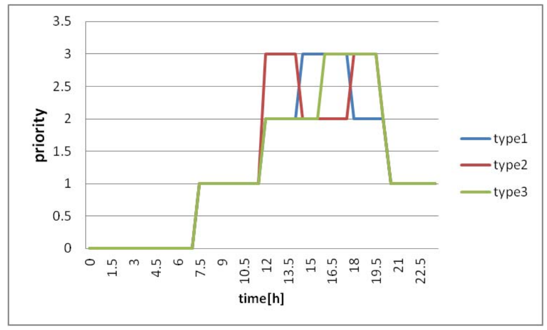

Fig. 5. Priority map for a washing machine

	initial point	$p_{request}$	request time	C
type1	100	3	7:30	0.3
type2	100	5	9:30	0.7
type3	100	7	2:30	0.8

TABLE I
USER'S TYPES AND THEIR PARAMETERS

shown in Fig.4. The initial plan includes the power usage of air conditioners and water heaters, which is previously defined as s_i. The initial plan also contains the power usage of IH cooking stoves, which is not controlled by demand response.

The priority map indicates time slots in which the user wants to use washing machines. The agent selects the available time slots with highest priority, and reserves them for using a washing machine.

The power company gathers the day's use plans for electric appliances via users' smart meters. Next, the power company executes the peak shift and power savings by the reservation trade method and the optimization of power savings to restrict peak power. Negotiations for the reservation trade are performed by agents of the smart meters and by the leader. The demand response is executed, the day's use plans for electric appliances are updated in accord with the total demand schedule every 30 minutes.

III. Experiments

We assumed three types of users, which are shown in TABLE I. The initial point is the amount of points that a user possesses when the experiment starts. Request time is the time slot at which a user begins to make reservations. In addition, priority maps of each type maps are shown in Fig.5, and parameters of electric appliances are shown in TABLE II.

We used a computer with a memory of 192GB and Xeon X5675 (6 Core, 3.06GHz)×2. We assume that we have an unlimited number of computers, and we estimate the computation time in the case that it is fully distributed and parallelized.

The computation time of the centralized system and the hierarchical system were compared. The results for the total number of users (1000 households) are shown in Figs.6 and 7, where vertical axes indicate computation time and horizontal axes represent time slots. The results for the total users equals 10,000 households and are shown in Figs.8 and 9.

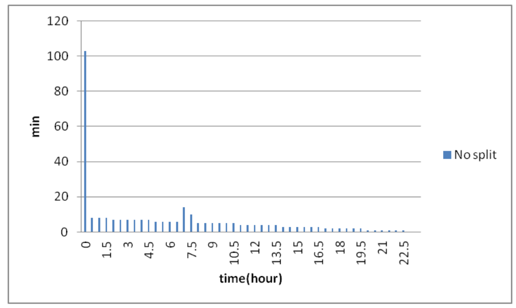

Fig. 6. Computation time(the centralized system)[number of users!′1000]

In the centralized system, the computation time becomes high in time slots in which many users make reservations. In the hierarchical system, the computation time is significantly reduced. In particular, computation time for the centralized system is > 30 min in many time slots when $N = 10,000$ households.

The reduction of peak power of the centralized and hierarchical systems were compared. The number of agents in the 2nd layer is 1/10 of the number of user agents. The result is shown in Fig. 10, where "normal" indicates the original power demand, and "no split" and "split" are the power demand managed by the centralized system and the hierarchical system, respectively.

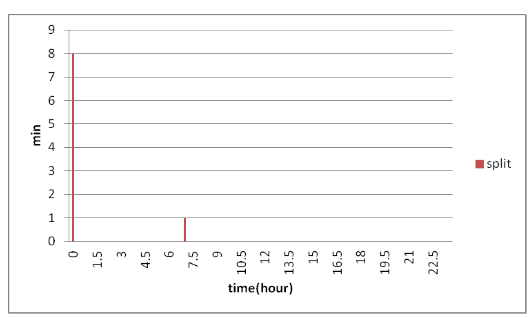

Fig. 7. Computation time(the hierarchical system)[number of users!′1000]

	control method	power(kWh/30min)	condition
washing machine	reservation trade	0.35kWh	rule of reservation trade method
water heater	optimization	0.75kWh!Æ0kWh	total power(1 day):3kWh
air-conditioner	optimization	1.5kWh!Æ0kWh	No power-saving for 1 consecutive hours
refrigerator	No control	0.06kWh!Æ0kWh	boot all day
IH	No control	0.5kWh!Æ0kWh	boot in a particular time

TABLE II
PARAMETERS OF HOME ELECTRONICS

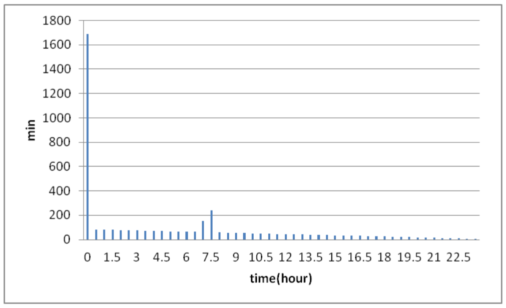

Fig. 8. Computation time(the centralized system)[number of users!′10000]

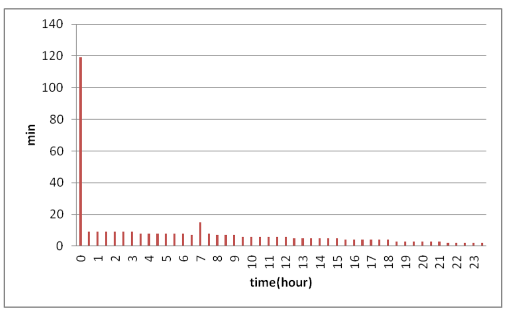

Fig. 9. Computation time(the hierarchical system)[number of users!′10000]

We obtained a successful reduction of peak power by configuration of limited power. But the reduction of peak power with the centralized system was better than that obtained with the hierarchical system. This is because optimization in the hierarchical system is performed within each group, which is not exactly equivalent to the global optimization. Accordingly, there is a trade-off between computation time and power reduction.

We compared computation time while varying the number of splits. The results for 1000 users are shown in Fig. 11, and results for 10,000 users are shown in Fig. 12. Reduction of computation time is achieved by increasing the number of splits.

Next, we compare the reduction of peak power obtained by varying the number of splits. The results for 1000 users are shown in Fig. 13, and results of 10,000 users is shown in Fig. 14. We found that the reduction of peak power was reduced with an increase in the number of splits.

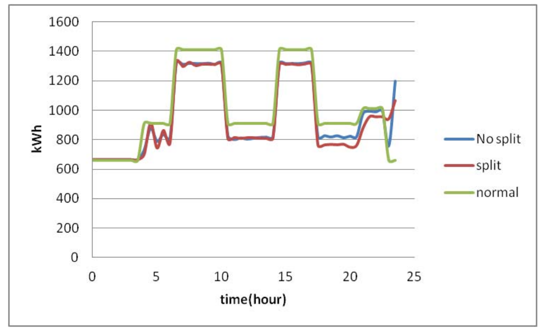

Fig. 10. Power demand (No split and split)[number of users!′1000]

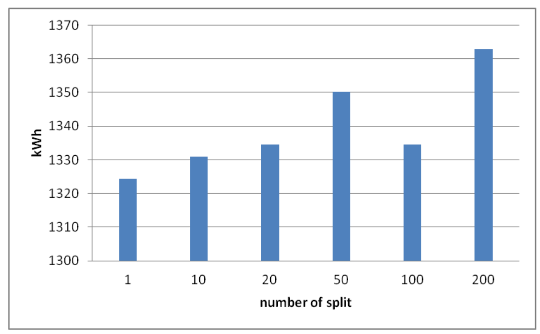

Fig. 11. Peak power[number of users!′1000]

IV. CONCLUSION

A mechanism called demand response, which manages a users' consumption of electricity according to supply conditions at peak demand, becomes the focus for managing the

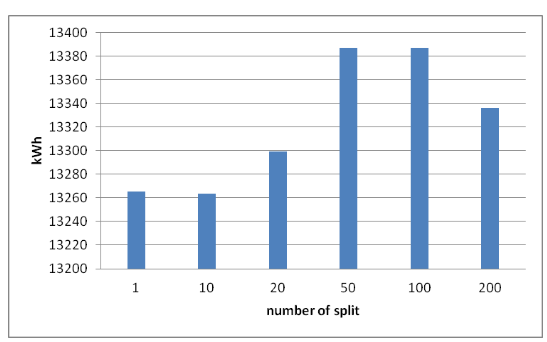

Fig. 12. Peak power[number of users!′10000]

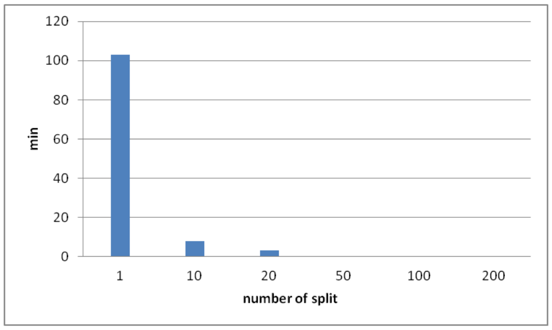

Fig. 13. Computation time[number of users!′1000]

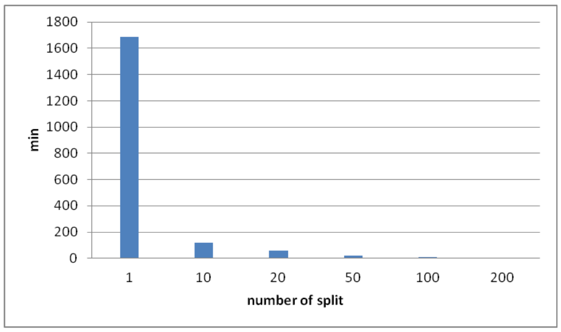

Fig. 14. Computation time[number of users!′10000]

balance between supply and demand. Because the electric power company must provide service to an immense number of users, computing time will increase and the flexibility of the real-time system will be lost in the centralized system. In this paper, we investigated approaches to real-time, large-scale demand response.

The method divides the large-scale problem into a solution using a hierarchical structure for distributed processing. This structure consists of three layers. Users form the bottom layer, and the second layer consists of the leaders of the user group. A plant agent in the top layer manages the leaders. The role of the plant agent is to understand and manage the entire demand. In addition, processing is distributed so that each parent node manages a group of child nodes. A real-time flexible system was built using the hierarchical structure, and it was compared with the centralized system. In addition, the reservation trade method and the amount of power savings are employed as a demand-response system.

The proposed method achieved a successful reduction in peak power using a configuration of limited power, and computation time was significantly reduced in the hierarchical system. Greater the number of splits more the reduction in computation time. However, the reduction of peak power deteriorates when the number of splits is larger than 20. The method is acceptable when the number of splits is within the range of 10 to 20, as shown by the low peak power and a low computation times observed in the experimental results.

Applying the proposed method to real-world system is a future work. In addition, the reduction of peak power can be improved in the hierarchical system.

REFERENCES

[1] Tsuzuki Kazuhiro, Moriyama Ryo, Ishimoto Yuki, Tokimatsu Koji and Hagiwara Naoto, A Study on Japanese Energy Balances after the Great East Japan Earthquake, Journal of the Japan Institute of Energy 91(2), 104-110, 2012-02-20

[2] Yokoyama Akihiko, Development of Smarter Grid (I), The journal of the Institute of Electrical Engineers of Japan 130(2), 94-97, 2010-02-01

[3] Ogimoto Kazuhiko, Power System in Low-Carbon Society, The journal of the Institute of Electrical Engineers of Japan 129(1), 16-19, 2009-01-01

[4] US Department of Energy, Benefits of demand response in electricity markets and recommendations for achieving them,2007.

[5] Chengjian Wei, Hengkai Hu, Qinghua Chen and Guang Yang ,Learning Agents for Storage Devices Management in the Smart Grid, Computational Intelligence and Software Engineering (CiSE), 2010

[6] Ninghui Zhu, Xiaomin Bai, Junxia Meng, Benefits Analysis of All Parties Participating in Demand Response, Power and Energy Engineering Conference (APPEEC),2011

[7] 2008 Housing, Land Survey, Statistics Bureau, Director-General for Policy Planning (Statistical Standards) and Statistical Research and Training Institute

[8] Leyli Mohamad Khanli, Saeed Ebadi, A New Distributed and Hierarchical Mechanism for Service Discovery in Grid Environment, LECTURE NOTES IN COMPUTER SCIENCE,2010